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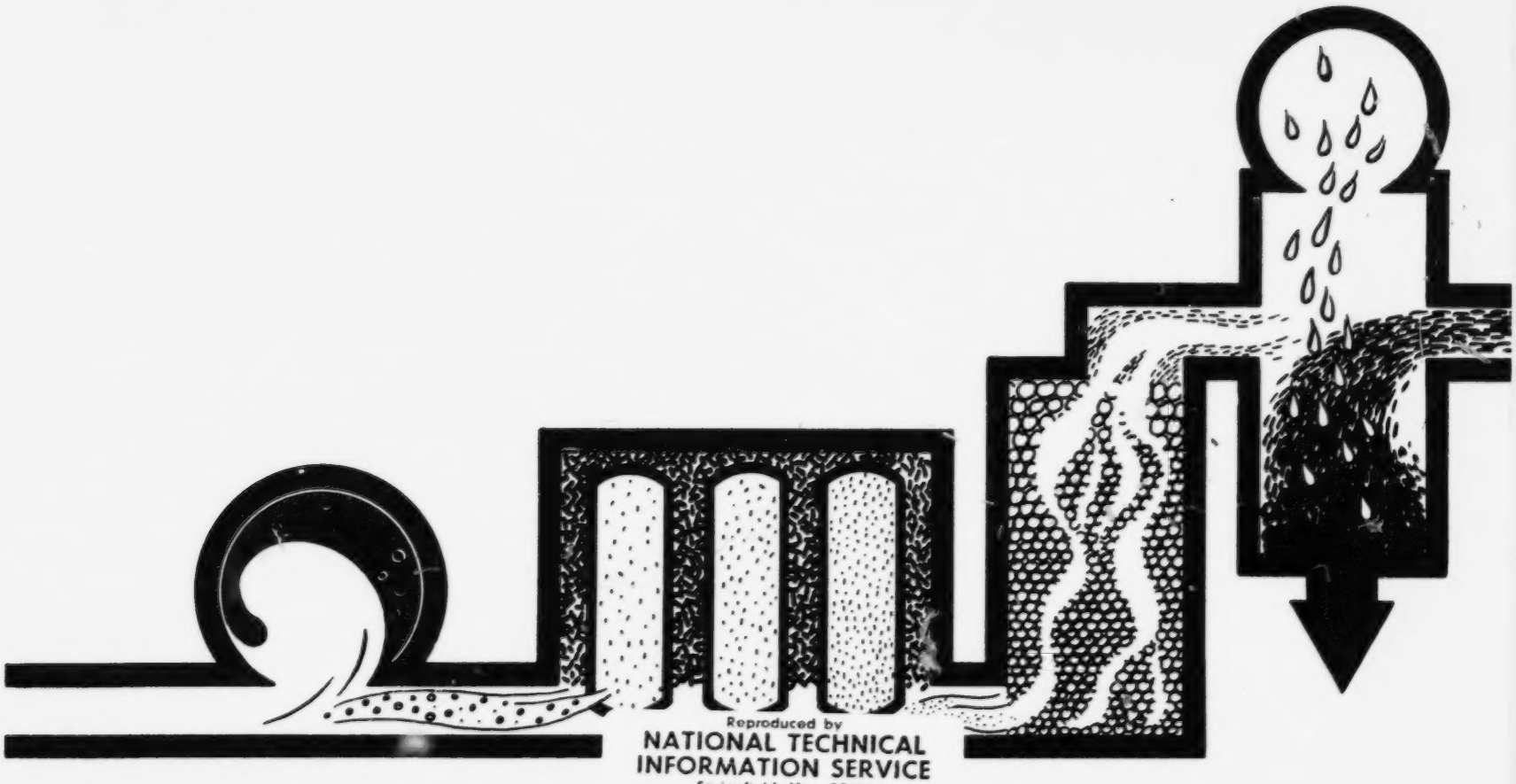
"THE DEVELOPMENT OF A FLUIDIZED-BED TECHNIQUE FOR THE REGENERATION OF POWDERED ACTIVATED CARBON"



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27 Abstract Results of research conducted at the Columbus Laboratories of Battelle Memorial Institute on the regeneration of spent powdered carbon is described. The study was directed toward the development of a fluidized-bed regeneration technique in which two systems were investigated. One was a system in which the dried spent carbon was regenerated during its passage through a fluidized-bed of inert material while the other system consisted of a pulsating fluidized-bed system in which the finely divided regenerated carbon served as the bed material. Although both systems restored the spent powdered carbon to 90% of its original adsorptive capacity and recovered 80% by weight, the fluidized inert bed was chosen for larger scale development because of its higher unit capacity. A pilot-scale unit was designed and constructed to process 30 pounds of spent carbon in an 8 hour period. This unit was integrated in a powdered carbon adsorption process and tested for 23 days. The results indicated that regenerated carbon was as effective as virgin carbon for organic removal for at least 3.6 cycles through the system. An economic analysis indicated that operating costs would be about 1 cent per pound for a commercial plant producing 20,000 pounds of regenerated carbon per day. (Ellis-Texas)

(WRSIC abstract)

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THE DEVELOPMENT OF A FLUIDIZED-BED TECHNIQUE FOR THE REGENERATION OF POWDERED ACTIVATED CARBON

by

Battelle Memorial Institute
Columbus Laboratories
Columbus, Ohio 43201

for the

FEDERAL WATER QUALITY ADMINISTRATION

DEPARTMENT OF THE INTERIOR

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ABSTRACT

This report describes the results of research conducted at the Columbus Laboratories of Battelle Memorial Institute on the regeneration of spent powdered carbon. The study was directed toward the development of a fluidized-bed regeneration technique. Two fluidized-bed systems were considered during the course of the investigation: a system in which the dried spent carbon was regenerated during its passage through a fluidized bed of an inert material; and a pulsating fluidized-bed system in which the finely divided regenerated carbon served as the bed material. Both techniques were effective in restoring the spent powdered carbon to over 90 percent of its original adsorptive capacity. Recoveries in excess of 80 percent of the weight of the dried spent carbon were attained. However, because of its higher unit capacity, the fluidized inert bed system was selected for subsequent larger scale development.

On the basis of favorable results in the laboratory, a pilot-scale unit, 10-inch-ID, was designed and constructed to process 30 pounds of spent carbon in an 8-hour period. Operation of this system was integrated into the main powdered carbon adsorption process for evaluation of the combined system performance. The results of this operation covering a period of 23 days indicated that regenerated carbon was as effective as virgin carbon for organic removal from secondary effluent for at least 3.6 cycles through the system. Overall carbon losses averaged 15 percent per regeneration cycle.

A preliminary economic analysis indicated plant operating costs would be about 0.9 to 1.1¢ per pound of carbon for a commercial plant producing 20,000 pounds of regenerated carbon per day.

This report was submitted in fulfillment of Contract No. 14-12-113, Program No. 17020 FBD, between the Federal Water Quality Administration and Battelle Memorial Institute, Columbus Laboratories.

Key Words: Activated carbon
Regeneration
Fluidized bed

CONTENTS

	Page
INTRODUCTION	1
EXPERIMENTAL	5
Bench-Scale Studies	5
Description of Sample	5
Analytical Methods Employed	5
Apparatus and Procedure	7
Fluidized Inert Bed System	7
Pulsed Fluidized-Bed System	7
Results and Discussion	11
Effect of Temperature and Gas Composition	14
Effect of Retention Time	14
Effect of Increased Moisture Content in Feed	17
Losses of Carbon During Regeneration	18
Comparison of Fluidization Techniques	20
Design, Construction, and Operation of a Pilot-Plant Facility	21
Design	21
Construction	23
Operation	26
Procedure	26
Results and Discussion	26
Problems Encountered	33
DESIGN AND ECONOMIC CONSIDERATIONS	37
ACKNOWLEDGMENT	43

FIGURES

		Page
1	Powdered carbon adsorption system	2
2	Relationship between total carbon content and ultraviolet absorbence of treated and untreated secondary sewage effluent	6
3	Bench scale fluidized bed and auxiliary equipment	8
4	Photograph of complete bench-scale installation	9
5	Sketch of pulsed fluidized-bed apparatus	10
6	Effect of temperature on adsorption capacity in various atmospheres using inert bed system	15
7	Effect of temperature on recovery in various atmospheres using inert bed system	16
8	Effect of moisture content of spent carbon on the effectiveness of its regeneration at 1250 F	19
9	Heat and materials flow diagram for pilot regeneration system	22
10	Detailed drawing of the 10-inch-diameter fluidized-bed unit	24
11	Arrangement of equipment for pilot-plant regeneration study	25
12	Total organic carbon removal using regenerated powdered carbon	31
13	Turbidity removal from secondary effluent using regenerated powdered carbon	32
14	Fixed carbon, ash, and volatile content of regenerated carbon	35
15	Flow diagram of commercial regeneration system, employing conventional operation, example I	38
16	Flow diagram of commercial regeneration system employing offgas recycle, example II	39
17	Detailed drawing of commercial fluidized-bed regeneration unit	41

TABLES

No.		Page
1	SUMMARY OF REGENERATION EXPERIMENTS IN FLUIDIZED INERT BED SYSTEM	12
2	SUMMARY OF REGENERATION EXPERIMENTS IN PULSED FLUIDIZED-BED SYSTEM	13
3	EXPERIMENTAL DATA SHOWING THE EFFECT OF BED WEIGHT ON REGENERATION, INERT BED SYSTEM	17
4	DATA ON COMPOSITION OF VIRGIN, SPENT, AND REGENERATED CARBONS	20
5	EXPERIMENTAL DATA SHOWING CARBON LOSSES DURING SEVERAL REGENERATION EXPERIMENTS	20
6	MISCELLANEOUS DESIGN DATA	21
7	CONDITIONS EMPLOYED DURING PILOT-PLANT START-UP OPERATIONS	26
8	RESULTS OBTAINED DURING PILOT-PLANT START-UP OPERATIONS	27
9	AVERAGE OPERATING PARAMETERS DURING REGENERATION RUN	29
10	AVERAGE TOTAL ORGANIC CARBON (TOC) VALUES AND REMOVAL EFFICIENCY FOR EACH REGENERATION CYCLE	30
11	COMPARISON OF AVERAGE TOTAL ORGANIC CARBON REMOVAL BY VIRGIN AND REGENERATED CARBON	33
12	DAILY REGENERATED CARBON ANALYSES AND RECOVERY	34
13	CONDITIONS AND RESULTS OF EXAMPLE DESIGN CALCULATIONS FOR COMMERCIAL REGENERATION SYSTEM	37
14	CAPITAL COSTS FOR COMMERCIAL REGENERATION SYSTEM	40
15	OPERATING COSTS FOR COMMERCIAL REGENERATION SYSTEM	42

CONCLUSIONS AND RECOMMENDATIONS

A study of the regeneration of spent powdered carbon by fluidized-bed techniques has been completed. The study was concerned with an evaluation of bench-scale and pilot-scale systems and an economic assessment of a commercial system based on appropriate scale-up factors.

The results obtained during the study showed that efficient regeneration and recovery of spent powdered carbon can be achieved in a fluidized-bed system. Under proper operating conditions, the spent carbon could be regenerated to an active form as effective as virgin activated carbon in its ability to adsorb organic components from a typical secondary sewage effluent. Recovery of the regenerated carbon was about 85 percent per regeneration cycle.

On the basis of initial bench-scale studies, the following major conclusions were drawn:

(1) A system utilizing an inert bed of fluidized solids through which the fine carbon is passed or a system employing pulsation of the fine carbon solids are equally effective from a technical standpoint.

(2) A temperature between 1000 and 1500 F and a gas atmosphere containing nitrogen, oxygen, carbon dioxide, and water vapor are most effective for efficient regeneration of the spent carbon.

(3) Temperature is a primary variable; raising the temperature increases both the adsorptive capacity and the weight losses of carbon during processing.

(4) Oxygen content is also a primary variable and should be held to a minimum to reduce carbon losses through combustion.

(5) From a practical standpoint, the fluidized inert bed system is the most feasible because of higher unit capacity when processing a relatively wet spent carbon feed.

On the basis of a pilot-scale investigation of the process, it was concluded that:

(1) After 3.6 cycles of adsorption and regeneration, the regenerated carbon is almost as effective as virgin carbon in removing total inorganic materials from secondary sewage effluent.

(2) Average carbon losses per regeneration cycle can be expected to be less than 15 percent in a continuously operated system.

(3) The overall physical performance of the fluidized-bed regeneration unit was excellent.

Generally, it was concluded that the overall study was quite successful with the development of a satisfactory method for regeneration of spent powdered carbon. It therefore was recommended that the development of the process be continued on a larger scale. It also is recommended that immediate emphasis be placed on the continued economic appraisal of the process particularly on the economic advantages of powdered carbon compared to granular carbon systems.

This study has indicated that powdered carbon can be regenerated for about 0.9 to 1.1¢ per pound in a commercial system having a capacity of 20,000 pounds per day. Capital cost estimates for such a system range from $350,000 to $435,000.

INTRODUCTION

The use of powdered activated carbon for the tertiary treatment of secondary sewage effluents is being studied on a 10-gpm scale at Lebanon, Ohio, by the Advanced Waste Treatment Research Activities of the Federal Water Pollution Control Administration. A schematic diagram of the process is shown in Figure 1. FWPCA's pilot-plant study has shown that powdered carbon is as effective as granular activated carbon for removing the organic impurities from the wastewater.

Before powdered carbon can be used commercially for the tertiary treatment of sewage effluents, an economical method of regeneration must be developed. Investigations have been conducted on the thermal regeneration of spent carbon but neither the optimum process conditions nor operating procedures have been completely delineated.

In order to continue the development of a suitable regeneration system, Battelle Memorial Institute recommended a research program to examine the feasibility of applying fluidized-bed techniques for the regeneration of the spent carbon. The use of the fluidized bed for regeneration can offer the key advantages of excellent temperature and atmosphere control and the ability to process the powdered solids conveniently and continuously. However, the median diameter of the carbon particles is approximately 11 microns, which is considerably finer than normally used in fluidized-bed operations. The problems associated with fluidization of very fine powders are the inability to achieve proper fluidization and the high entrainment losses. Thus, the desired control of temperature and retention time is not achieved.

The application of fluidization methods for regeneration of powdered carbon therefore required the development of operating methods for proper fluidization of the fine powder or the development of an alternative procedure. Two techniques were recommended by Battelle to have sufficient merit for study:

(1) The use of a fluidized bed of coarse, inert particles which maintains a constant-temperature zone. The spent, dried, powdered carbon would be fed into the bottom of the coarse, inert bed and carried through the bed by the action of the fluidizing gas. This method of fluidized-bed operation would be expected to offer control of retention time of the fine carbon powder and show good heat-transfer characteristics. The finely divided carbon would be recovered from the effluent gas stream with cyclone collectors or some other collection device.

(2) The use of a fluidized bed of the powdered carbon to which vibration or pulsation is applied. This method would be expected to offer a minimum of fluidizing gas requirements and entrainment losses while achieving the excellent heat-transfer rates and temperature control afforded by the fluidized bed.

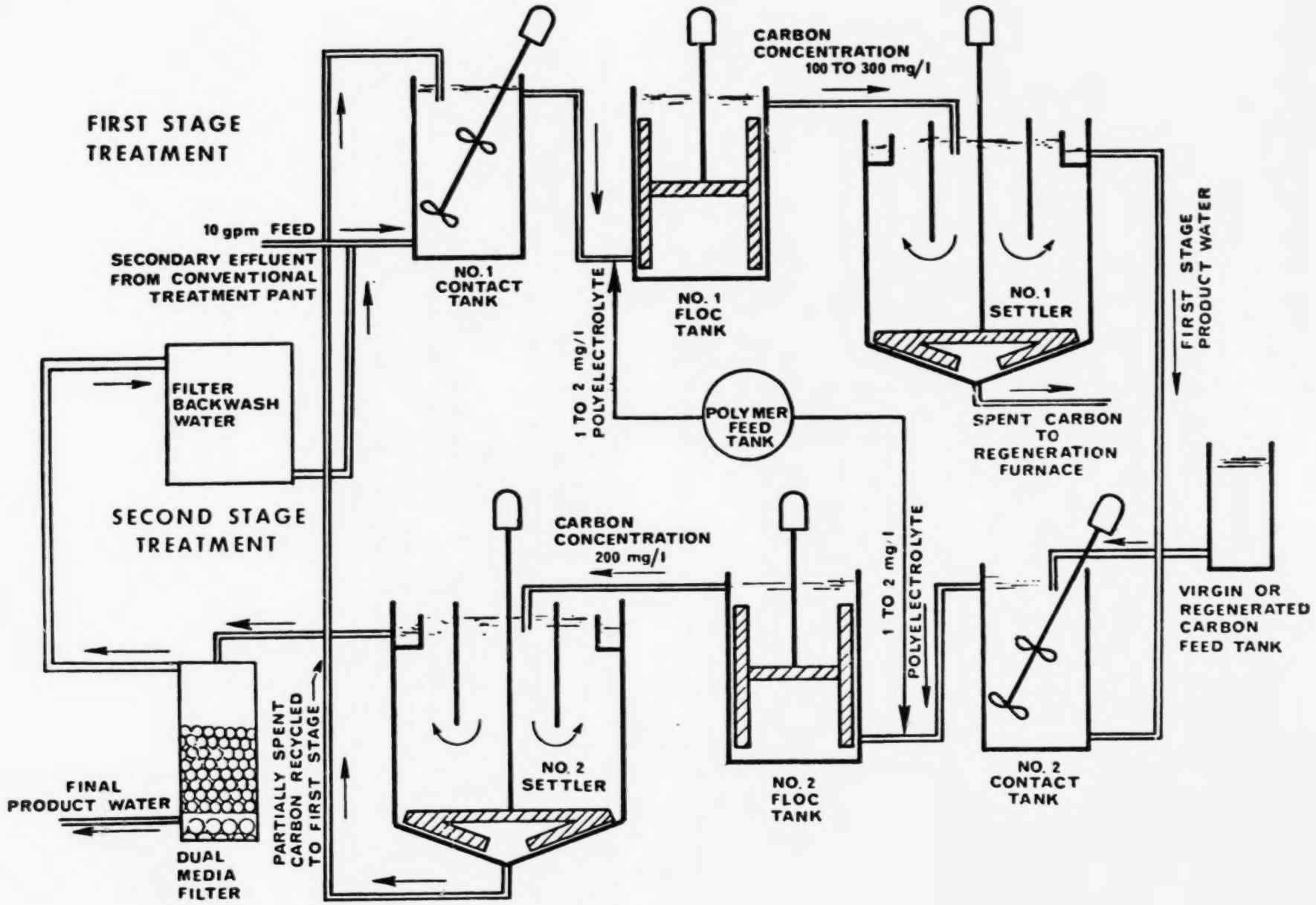

Figure I. Powdered carbon adsorption system

The proposed research program recommended by Battelle consisted of three phases of work:

(1) A bench-scale study of each of the two fluidized-bed techniques described above;

(2) The design, construction, and operation of a pilot-scale fluidized-bed unit;

(3) The preliminary design and economic assessment of a commercial fluidized-bed system.

Phase 1 of the program was initiated in July, 1967, and completed in April, 1968. A report summarizing this work was submitted May 10, 1968. On the basis of the initial study, the subsequent phases of work were approved and completed in February, 1970. This report summarized the major results and conclusions of the overall program.

EXPERIMENTAL

Bench-Scale Studies

Description of Sample

The spent carbon used as feed material during the initial experimentation was obtained from FWPCA's waste treatment pilot plant located at Lebanon, Ohio. The material was received as a slurry containing about 15 percent solids. The initial sample, 55 gallons, which was used for the majority of experiments, was pressure filtered and the solids dried at 90 to 100 C. Additional preparation of the dried solids included screening and ball milling for several minutes to break up agglomerates. A second spent carbon sample of approximately 10 gallons was used in several subsequent experiments designed to investigate the effect of high levels of moisture in the feed on regeneration characteristics. This sample also was pressure filtered but the filter cake was not oven dried. The moisture content of the sample was decreased to about 50 percent by air drying overnight. No attempt was made to eliminate agglomerates from this material.

Analytical Methods Employed

The technique used for determining the adsorptive capacity of the carbon samples was an empirical method based on ultraviolet (UV) absorbance measurement of secondary effluent samples treated with 200 mg per liter of carbon. The UV absorbance data before and after treatment with the carbon were used to calculate the relative adsorptive capacity of the regenerated carbon compared to that of virgin carbon. These results provided a measure of the degree of regeneration achieved during the experiments. No attempt was made, however, to relate these values to the organic loading capacity of the regenerated material. The procedure used in the analyses was as follows: the secondary effluent was treated with 200 mg per liter of carbon sample; after 30 minutes' contact time, the suspension was filtered through glass filter paper; the original secondary effluent after filtration and the clear filtrate were then measured by a Beckman DU spectrophotometer.

To provide additional data on the validity of the above method, several samples of treated and untreated secondary effluent also were analyzed for total carbon content with a Beckman carbon analyzer. The results obtained with the two analytical techniques are compared in Figure 2. The relationship obtained, although not entirely linear, shows a direct correspondence between the two methods of analyses. To provide a single basis for correlating the experimental data, all results were based on the ultraviolet absorbance method.

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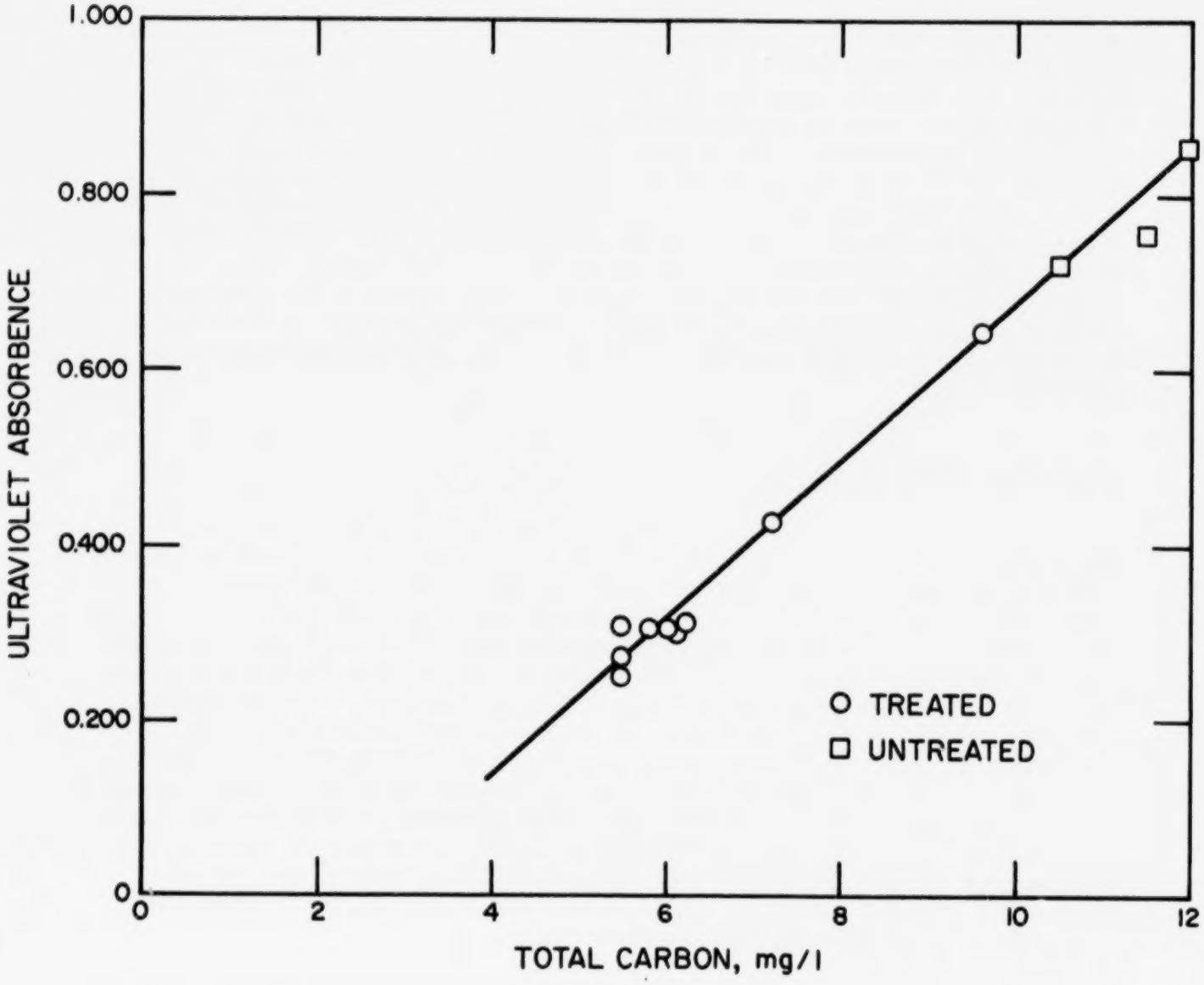

Figure 2. Relationship between total carbon content and ultraviolet absorbence of treated and untreated secondary sewage effluent

Apparatus and Procedure

Fluidized Inert Bed System. The major portion of the experimental program consisted of evaluating the first proposed fluidization technique in which a bed of coarse inert solids was used to provide a suitable regeneration environment. The experimental unit which was used in this part of the program comprised a 4-1/2-in. -ID by 24-in. long stainless steel vessel heated by an electric resistance furnace. For initial experimentation, a Thermal Dynamics fine powder feeder was used to introduce dried spent carbon into the fluidizing gas line. Regenerated products were collected in a cyclone dust collector followed by a small absolute filter. A sketch of the fluidized inert bed unit, together with some of the auxiliary equipment is shown in Figure 3. Figure 4 is a photograph of the complete installation.

During the experimentation, several modifications associated with the feed equipment and product collection train were made. To accommodate increased feed rates, two cyclones were installed in series and the absolute filter was replaced with either a porous stainless steel filter, 2.0-in. -O.D. by 3-ft. -long, or a 6-in. -O.D. column packed with glass wool. A water scrubber also was tried, however, excessive pressure drop and inefficient collection was experienced and the use of the scrubber was discontinued.

For those experiments in which spent carbon containing up to 50 percent moisture was used, a vibrating-type feeder manufactured by Vibra Screw Feeders, Inc., was employed. In these experiments, the spent carbon was introduced via an overhead feed tube which extended vertically into the bed.

The general procedure for making an experimental run was to charge the reactor with bed material and heat the unit to the desired operating temperature. In most cases, the bed comprised about 3300 grams of minus 35 plus 65 mesh sand or minus 20 plus 48 mesh flint shot. Spent carbon was fed into the unit and the regenerated products were collected in the cyclone and filter devices. After completion of a run, a material balance was made and samples of the various products were analyzed for adsorptive capacity.

Pulsed Fluidized-Bed System. The experimental unit which was used for a brief study on pulsation, the second technique proposed, was a specially designed, 4-in.-diameter unit also constructed of stainless steel. This unit contained a porous stainless steel gas distributor whereas the former unit contained a conical bottom section. The auxiliary pieces of apparatus including the cyclone and absolute filter dust collectors, the screw feeder, and the furnace equipment were identical to those used in the previous work. Figure 5 is a sketch showing the arrangement of major components of apparatus.

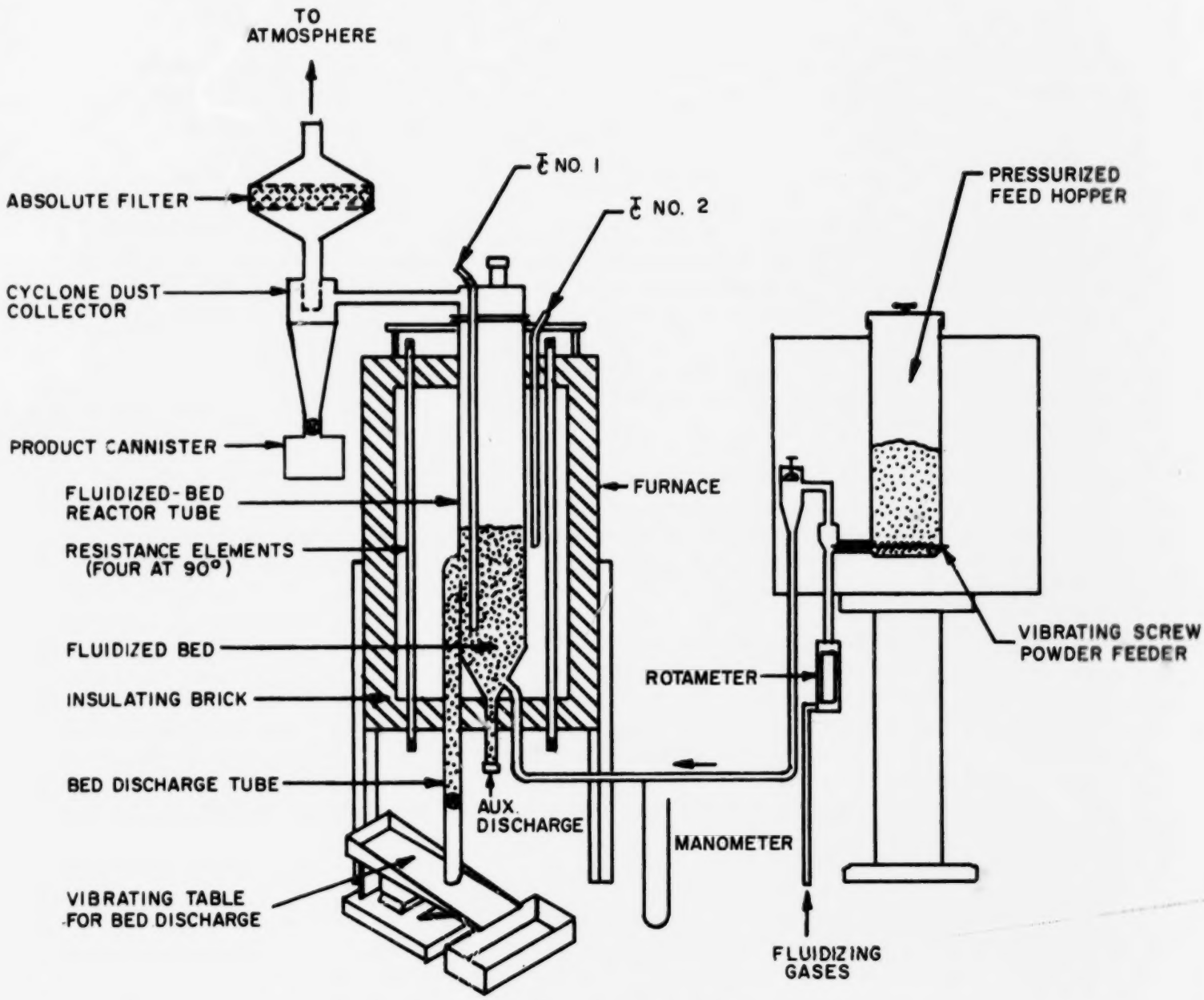

Figure 3. Bench scale fluidized bed and auxiliary equipment

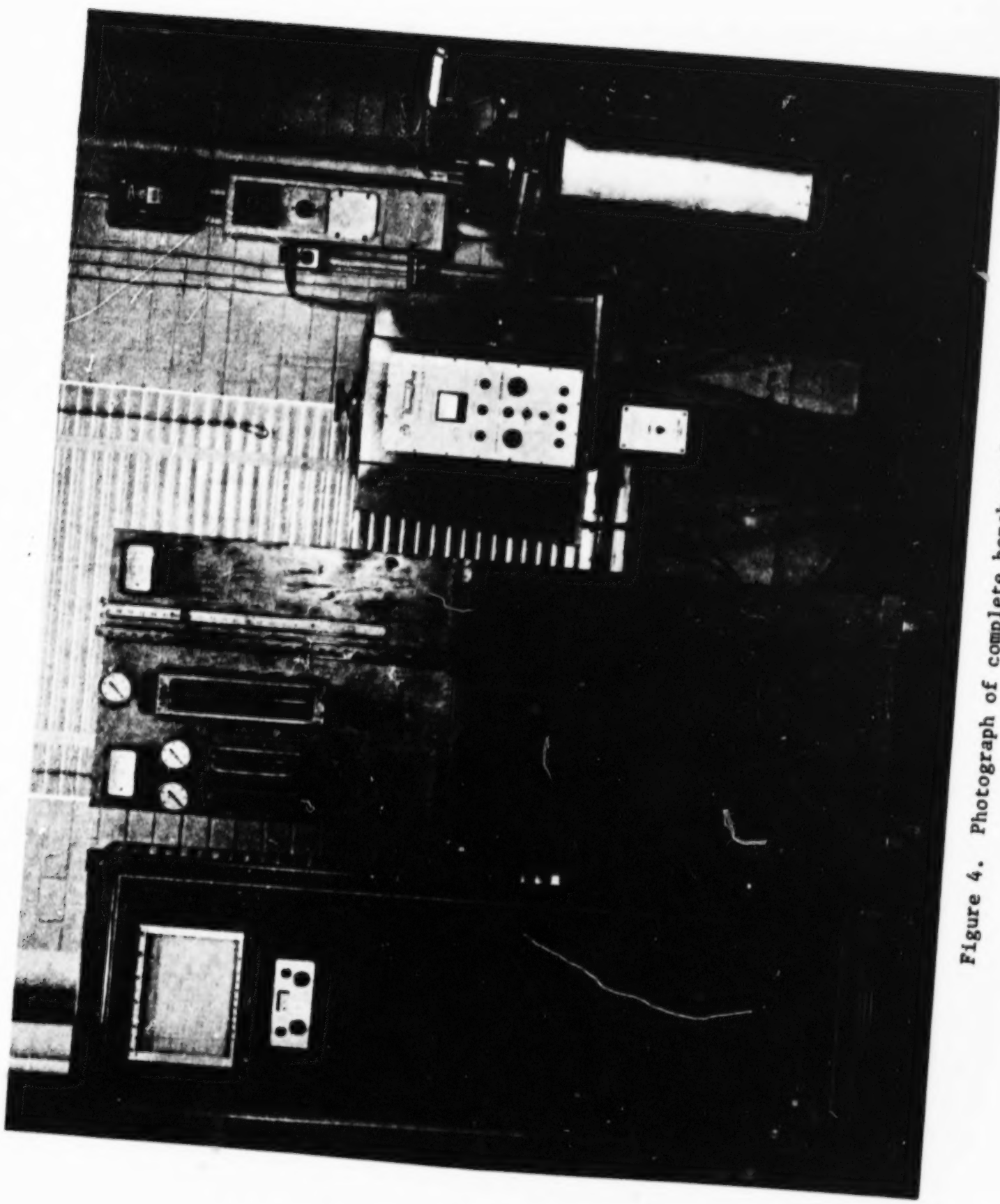

Figure 4. Photograph of complete bench-scale installation

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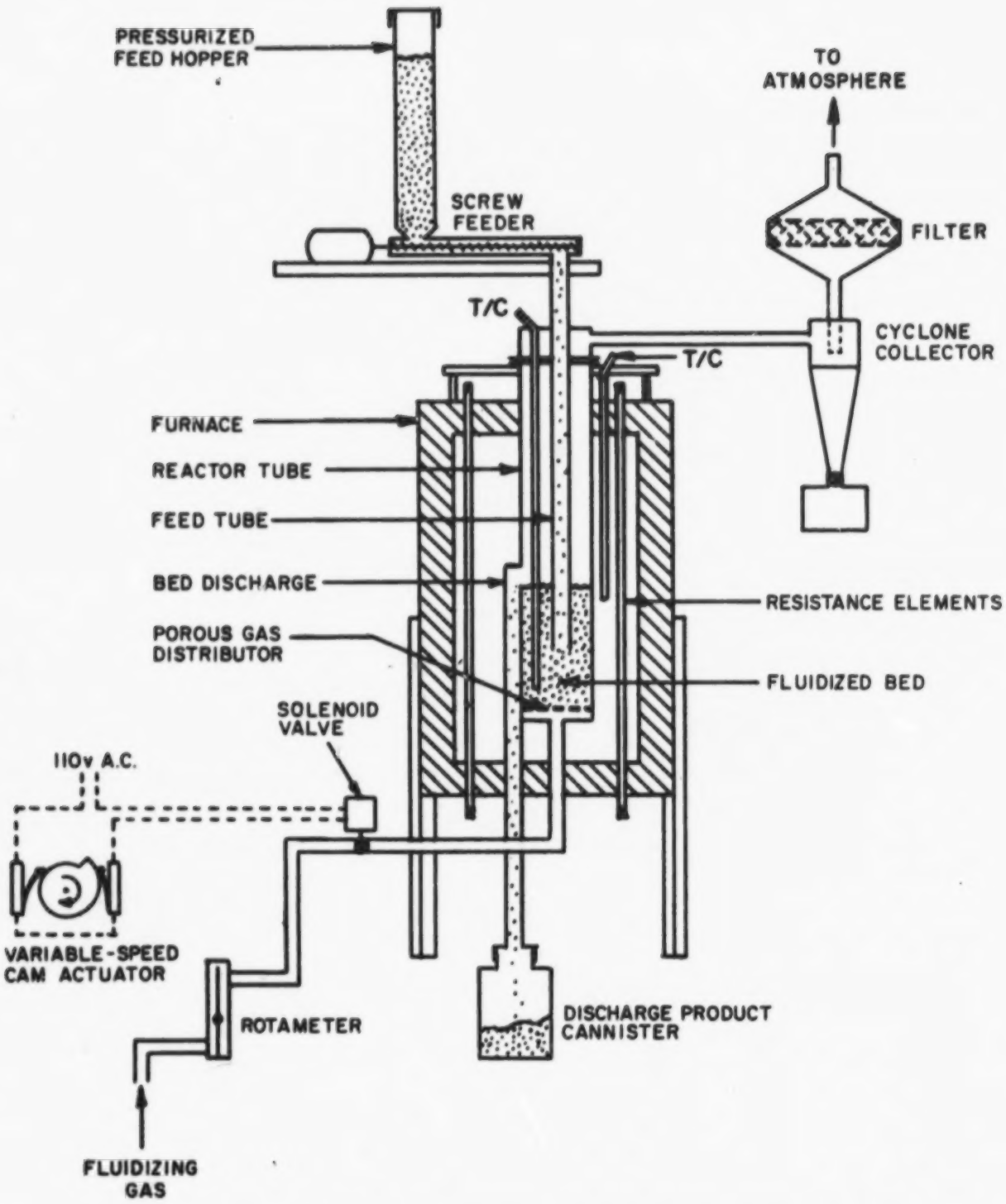


Figure 5. Sketch of pulsed fluidized-bed apparatus

Preliminary studies in this unit demonstrated that good fluidization of the fine carbon solids could be obtained by applying a pulsating gas flow to the bed. The pulsations were obtained by simply interrupting the flow of fluidizing gas at frequencies in the order of 400 to 500 pulses per minute. Several devices including a solenoid valve, a diaphragm valve, and rotary pulsator were evaluated for obtaining the pulsations and found to provide a comparable degree of fluidization. The solenoid valve shown in Figure 5 was used for the major portion of the experimentation. The valve was actuated by two microswitches following a variable speed, motor-driven cam.

Experimentation on the pulsed-bed technique comprised only a brief study of the effects of temperature and retention time on the degree of regeneration of the spent carbon. Initial experiments were conducted in a batchwise manner with no spent carbon being fed into the unit. The procedure used was to charge the unit with a starter bed of 100 to 220 grams of spent carbon. The bed was fluidized and heated to the desired operating temperature. Samples of the bed were withdrawn periodically via the overflow discharge during both the heat-up period and after various times at a steady temperature. These samples were analyzed for adsorptive capacity and the data used to develop approximate conditions, i.e., temperature and retention time, for efficient regeneration. Based on the results obtained during the preliminary operation, subsequent experiments were made during which spent carbon was continuously fed to the unit.

Results and Discussion

The primary objective of the experimental program was to investigate the effects of the operating variables on the degree of regeneration and recovery of the powdered carbon. Major emphasis was placed on a study of the inert bed system with only brief study of the pulsation technique. The major variables examined during the program and range of study were as follows:

(1) Temperature: 500-1500 F

(2) Composition of the fluidizing gas: selected mixtures containing N_2, O_2, CO_2, and H_2O

(3) Bed weight: 0-6720 grams

(4) Bed depth: 0-11.5 inches

(5) Moisture content of feed: 4.5-50 percent of H_2O

The experimental study consisted of a total of 37 runs in the fluidized inert bed system and 7 runs in the pulsed bed apparatus. Significant data from these experiments are summarized in Tables 1 and 2.

TABLE 1. SUMMARY OF REGENERATION EXPERIMENTS IN FLUIDIZED INERT BED SYSTEM

Expt. No.	Temp, F	Gas Composition	Gas Flow, scfm	Bed Weight, g[a]	Feed Weight, g[b]	Average Feed Rate, g/min[b]	Moisture in Feed, percent	Relative Adsorptive Capacity[c]	Weight Recovery, percent[b]
5	1500	90% N_2: 10% CO_2	1.0	3000	85	0.8	≈4.5	102	--
7	1000	90% N_2: 10% CO_2	1.2	3000	121	1.1	≈4.5	68	--
8	1250	90% N_2: 10% CO_2	1.1	3000	44	1.7	≈4.5	86	--
9	1000	Air	1.2	1000	180	1.5	≈4.5	91	--
10	1000	Air	1.2	2000	218	2.2	≈4.5	93	62
11	1000	Air	1.2	0	118	2.0	≈4.5	94	69
13	1000	N_2	1.2	2000	201	2.7	≈4.5	71	78
19	1500	80% N_2: 20% H_2O	1.1	3282	220	2.7	≈4.5	110	76
20	1250	80% N_2: 20% H_2O	1.1	3300	220	2.8	≈4.5	93	83
21	1000	80% N_2: 20% H_2O	1.1	3300	220	2.4	≈4.5	86	91
22	1000	Air	1.4	3300	301	52.8	≈4.5	100	57
23	950	Air	1.4	3300	344	22.9	≈4.5	86	76
24	1000	96% N_2: 4% O_2	1.4	3300	344	18.1	≈4.5	83	88
25	1000	98% N_2: 2% O_2	1.4	3300	344	17.2	≈4.5	78	90
26	1200	98% N_2: 2% O_2	1.4	3300	344	22.9	≈4.5	83	87
27	1500	98% N_2: 2% O_2	1.4	3300	344	22.9	≈4.5	97	81
28	1000	Simulated Combustion Gases[d]	1.4	3300	344	21.5	≈4.5	85	91
29	1250	Simulated Combustion Gases[d]	1.5	3300	344	24.6	≈4.5	92	85
30	1500	Simulated Combustion Gases[d]	1.5	3300	344	16.4	≈4.5	99	84
31	1000	Simulated Combustion Gases[d]	1.5	6720	344	21.5	≈4.5	81	90
32	1000	Simulated Combustion Gases[d]	1.5	0	68	9.6	≈4.5	55	91
33	1250	Simulated Combustion Gases[d]	1.5	3300	2601	14.9	≈4.5	92-99	88
34	1250	Simulated Combustion Gases[d]	1.4	3300	433	22.7	25.0	92	79
35	1250	Simulated Combustion Gases[d]	1.4	3300	433	19.5	33.3	82	80
36	1250	Simulated Combustion Gases[d]	1.4	3300	1022	30.5	50.7	71	80
37	1500	Simulated Combustion Gases[d]	1.2	6600	456	26.6	48.1	83	77

(a) In Experiments 5 through 21, -35+65 mesh sand was used. In Experiments 22 through 37, -20+48 mesh flint shot was used.

(b) Reported on a dry basis.

(c) Relative adsorptive capacity = 100 X

$$\frac{\text{difference in UV absorbance of secondary effluent before and after treatment with regenerated carbon}}{\text{difference in UV absorbance of secondary effluent before and after treatment with virgin carbon}}$$

(d) Gas mixture contained approximately 70% N_2, 10% CO_2, 2% O_2, and 18% H_2O. In Experiments 34 through 37, however, water vapor was not added because of the high moisture content of feed.

TABLE 2. SUMMARY OF REGENERATION EXPERIMENTS IN PULSED FLUIDIZED-BED SYSTEM

Expt. No.	Starter Bed,[a] g	Gas Composition	Sample Designation	Elapsed Time, min.	Temp, F	Gas Flow, scfm	Relative Adsorptive Capacity[b]	Weight Recovery, percent
2	143	Air	Spent carbon	0	70	0.25	27	
			A	10	500	0.21	38	
			B	13	750	0.21	62	
			C	21	1000	0.21	83	
			D	36	1000	0.21	102	67
4	96	90% N_2 10% CO_2	Spent carbon	0	70	0.10	31	
			A	15	500	0.10	-24[d]	
			B	22	750	0.10	61	
			C	32	1000	0.10	82	
			D	62	1000	0.10	87	
			E	92	1000	0.10	85	
			Final bed	--	--		82	83
6	48	Air	Discharge	30[c]	1000	0.08	80-90	
			Final bed				94	86
7	48	Air	Discharge	47[c]	1250	0.08	85-91	
			Final bed (+35 mesh)				96	
			Final bed (-35 mesh)				89	
			Cyclone dust				45	83

(a) Starter bed was dry spent carbon.
(b) See footnote (c) of Table 1.
(c) Continuous feeding period.
(d) A minus value indicates UV absorbance decreased after secondary effluent was treated with carbon sample.

Effect of Temperature and Gas Composition. Of initial interest during the study was an evaluation of temperature effects and gas composition on the regeneration efficiency. Included in this part of the investigation was a series of experiments conducted in the fluidized inert bed system at a fixed gas composition and at temperatures ranging between 1000 and 1500 F.

The effect of temperature on the relative adsorptive capacity of the regenerated products during these experiments is shown in Figure 6. Figure 7 shows the weight losses which occurred during regeneration. As shown, the same trend was noted with various regeneration atmospheres, i.e., both the adsorptive capacity and the weight loss increased with increasing temperatures within the range studied. Slightly better overall results (higher ratio of adsorptive capacity to weight loss) were obtained when simulated combustion gases were used for regeneration. These results also show that temperatures of 1500 F were required to produce a regenerated product equal in adsorptive capacity to that of virgin carbon. For maximum process economy, however, a lower temperature may be desirable in order to obtain a greater recovery of product with only a slight reduction in adsorptive capacity.

Although the study was limited, the results from the pulsed fluidized-bed experimentation also indicated a similar effect of temperature on regeneration as that shown by the results of the fluidized inert bed experimentation. In Experiment 2, Table 2, for example, it was found that some degree of regeneration occurred at temperatures as low as 500 F when air was the fluidizing medium; however, a temperature of 1000 F and a retention time of 15 minutes was required to achieve complete regeneration.

In the two experiments in which both feed introduction and product discharge were contiruous, Experiments 6 and 7, values for adsorptive capacity and weight recovery were comparable to those shown in Figures 6 and 7. Thus a similar performance of the two systems was obtained.

Effect of Retention Time. In order to evaluate the effect of retention time of the fine carbon in the fluidized-bed zone on its regeneration and recovery, experiments were made in the fluidized inert bed system at various bed weights ranging from 0-6720 grams of sand. Changes in bed depth were used to vary the retention time rather than changes in gas velocity primarily because of the wider variations which could be studied. Experiments also were conducted with no bed material present to evaluate the effectiveness of the inert bed compared to a simple heated tube reactor void of bed material.

Experimental data obtained during these experiments are compared in Table 3. In the initial series of experiments, low feed rates were used and the regeneration atmosphere was air. In the second series of experiments, simulated combustion gases were used and feed rates were increased by a factor of 10. The results of the experiments indicate that doubling the bed depth had no significant effect either on recovery or degree of regeneration when dry spent carbon was used. Thus, no improvement was

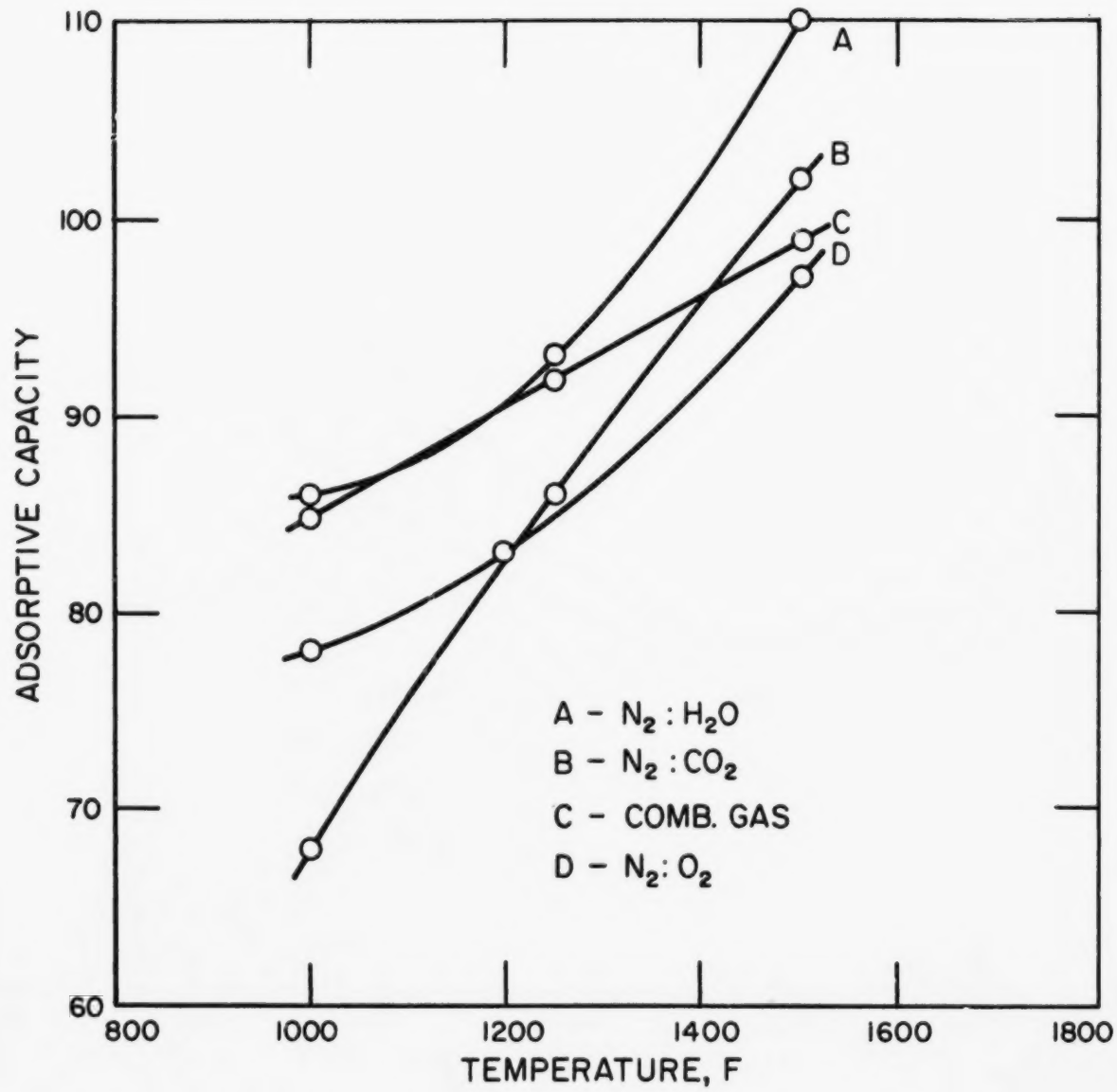


Figure 6. Effect of temperature on adsorption capacity in various atmospheres using inert bed system

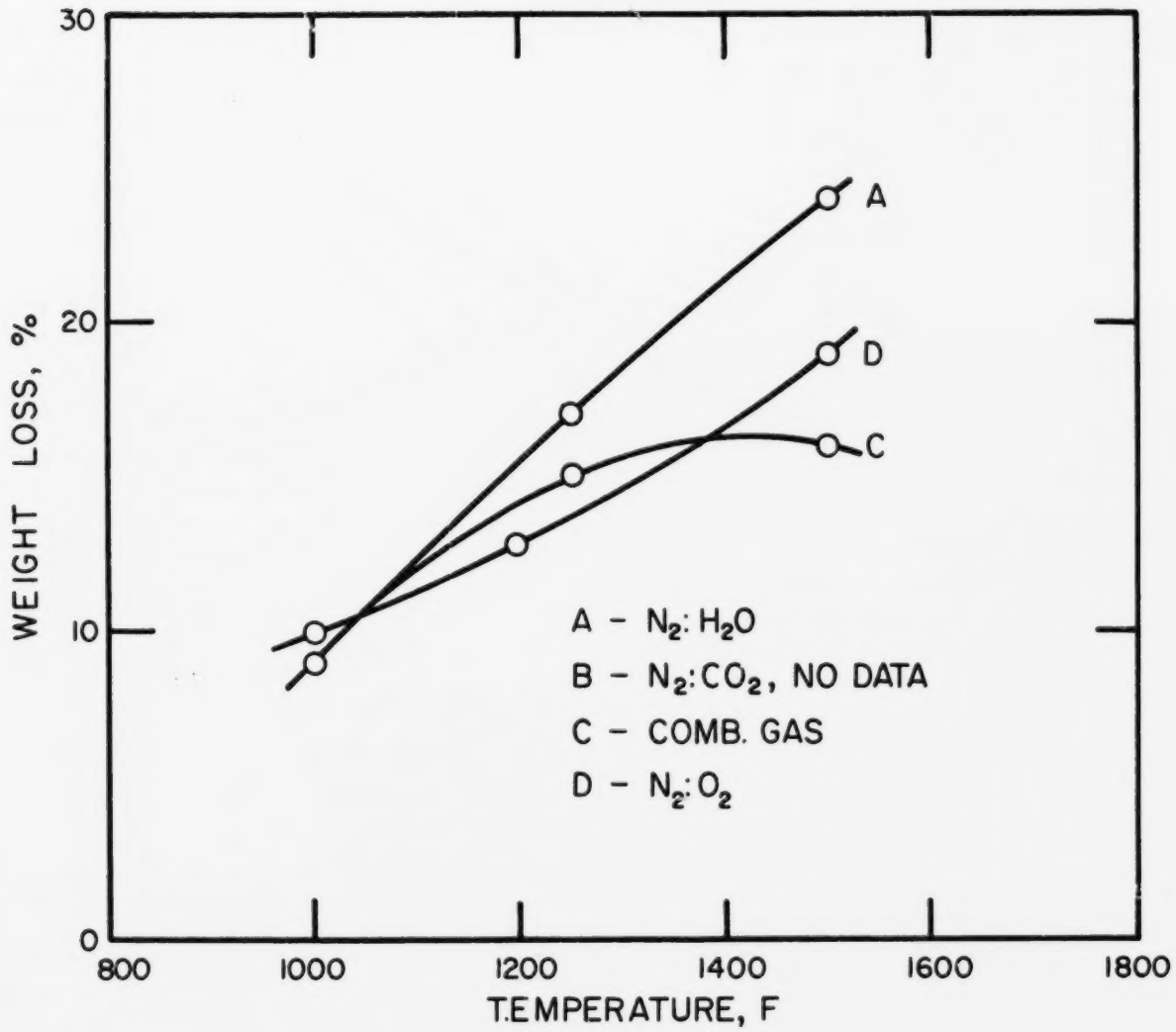


Figure 7. Effect of temperature on recovery in various atmospheres using inert bed system

noted when increasing the retention time in the fluidized inert bed system.

TABLE 3. EXPERIMENTAL DATA SHOWING THE EFFECT OF BED WEIGHT ON REGENERATION, INERT BED SYSTEM

Expt. No.	Temp, F	Gas Composition	Average Feed Rate, g/min[a]	Weight, g	Relative Adsorptive Capacity	Weight Recovery, percent[a]
9	1000	Air	1.5	1000	91	--
10	1000	Air	2.2	2000	93	62
11	1000	Air	2.0	0	94	69
28	1000	Simulated combustion gas	21.5	3300	85	91
31	1000	Simulated combustion gas	21.5	6720	81	90
32	1000	Simulated combustion gas	9.6	0	55	91

(a) Feed rate and recovery calculated on dry basis.

It was anticipated that the significant effect obtained during these experiments would be a loss in regeneration effectiveness when a heated reactor void of bed material was used. As can be seen from the data, this effect occurred in Experiment 32 where a value of 55 was obtained for the relative adsorptive capacity compared to a value of 85 obtained in Experiment 28. Thus, the presence of the inert bed resulted in a significant improvement in regeneration effectiveness. The fact that a similar effect was not obtained in the first series of experiments is believed due to the use of much lower feed rates. At low feed rates, the importance of high heat-transfer characteristics probably would be minimized; thus comparable regeneration would be obtained with or without the sand bed.

Effect of Increased Moisture Content in Feed. Although the original scope of the program was to investigate regeneration characteristics of dry spent carbon, this was modified subsequently to include a study of regeneration of relatively wet spent carbon containing up to 50 percent moisture. This level of moisture was considered typical of that which would be obtained from pilot-plant drying equipment to be used in future work.

This part of the study comprised four regeneration experiments in the fluidized inert bed system with spent carbon containing from 25 to 50 percent moisture. For the initial experiments (at 25 and 33.3 percent moisture), the feed material was prepared by adding sufficient water to dried spent carbon. The remaining two experiments were conducted with

spent carbon from a second batch of slurry which was filtered and the filter cake allowed to air dry overnight at ambient temperatures to approximately 50 percent moisture.

Some difficulty was encountered in feeding the relatively wet spent carbon with the screw feeder which was used in previous experiments. A vibrating-type feeder manufactured by Vibra Screw Feeders, Inc., proved satisfactory, however, for feeding materials containing up to 50 percent water. The original method of introducing feed into the unit which involved entrainment in the fluidizing gas also was changed to an overhead feed tube arrangement similar to that used in the pulsed fluidized-bed unit.

The experimental conditions, which were used in this investigation and the results which were obtained were previously shown in Table 1. The effects of spent carbon moisture content upon the relative adsorptive capacity (within the 25-50 percent range) also are shown in Figure 8. These results show that adsorptive capacity is inversely proportional to the moisture content upon regeneration at 1250 F. Although an adverse effect on regeneration was noted, the results of Experiment 37, Table 1, indicate that increasing the bed depth and/or the regeneration temperature may offset the effect of increased moisture in the feed. Because of time limitations this effect could not be fully evaluated during the bench-scale experimentation.

Losses of Carbon During Regeneration. Because of the importance of the efficiency of carbon recovery to the economic feasibility of the regeneration process, considerable effort was directed toward the development of basic information on this aspect of the process. Previously shown in Figure 7 were the effects of the operating variables on the degree of recovery of regenerated carbon. These results were based on the weights of the various products recovered during the experiments. This method, however, does not account for differences in the moisture and ash contents of the feed and product materials nor for the adsorbed organics and adsorbed gases present in the materials.

In order to develop additional information on the actual losses of carbon during regeneration, samples of virgin carbon, spent carbon, and regenerated carbon were analyzed to determine their carbon, hydrogen, and ash contents as well as the loss in weight when dried at room temperature under a vacuum. The results of these determinations are shown in Table 4. These data show that the actual carbon content of the samples varied considerably and that significant amounts of moisture and/or adsorbed gases were present.

Several experiments also were conducted during which samples of the exhaust gas were analyzed for CO_2 by gas chromatography. The gas analyses were used to calculate the loss of carbon by reaction with components of the gas phase.

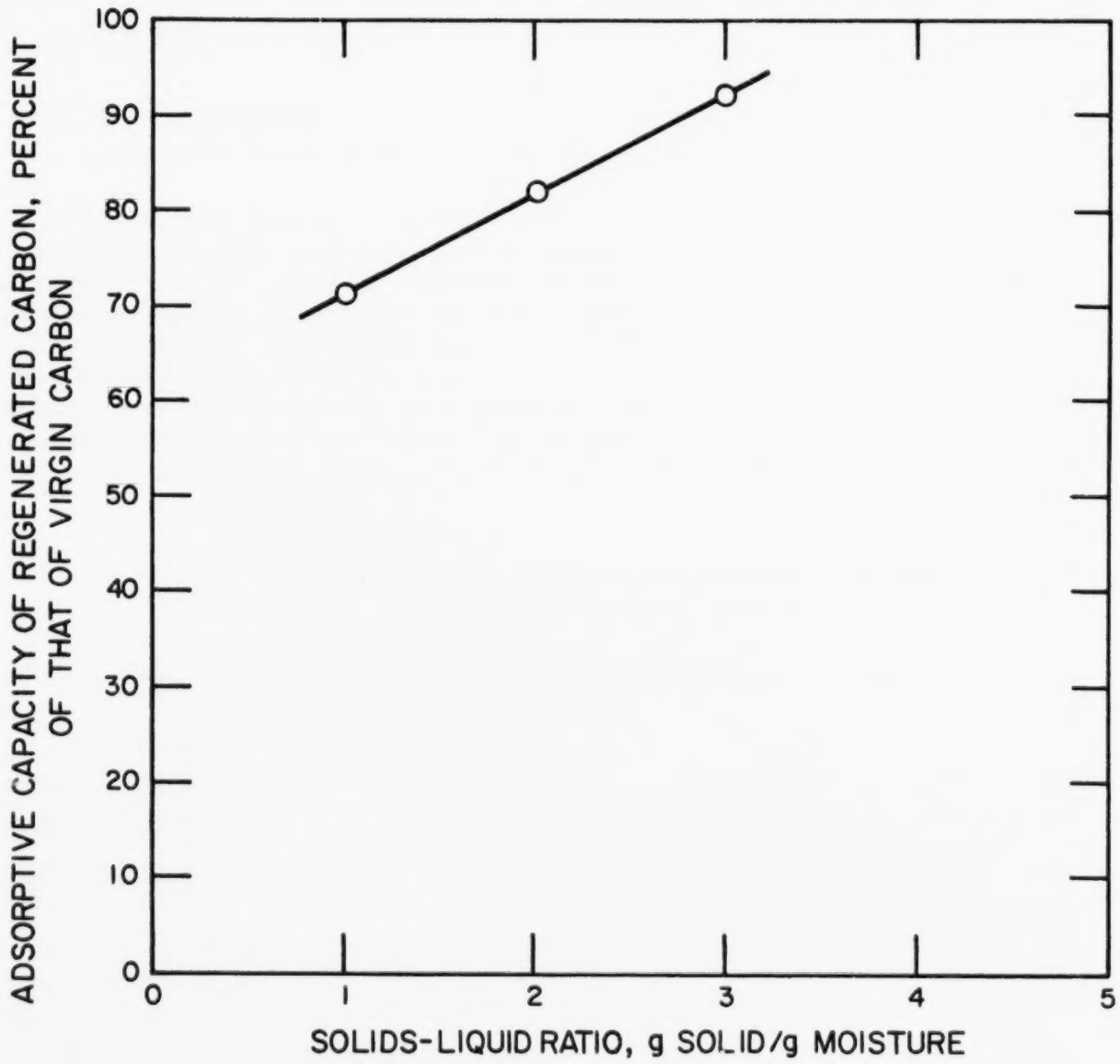


Figure 8. Effect of moisture content of spent carbon on the effectiveness of its regeneration at 1250F

TABLE 4. DATA ON COMPOSITION OF VIRGIN, SPENT, AND REGENERATED CARBONS

	Composition, percent				
	Loss of Weight[a]	Carbon	Hydrogen	Ash	Volatiles
Virgin carbon	6.96	80.9	0.84	4.55	6.75
Spent carbon	4.42	76.2	1.48	8.08	9.82
Regenerated carbon, Expt. No. 5	0.34	86.7	0.93	9.73	2.30

(a) Samples were specially dried at room temperature in vacuum.

The results obtained from these experiments are shown in Table 5. These data show that, with air for regeneration at 1000 F and at low feed rates, the actual loss of carbon as CO_2 is relatively high. When the available oxygen was decreased and the feed rate was increased in Experiment 24, however, carbon losses were decreased significantly. The losses in weight during the latter experiments at low oxygen levels (10-19 percent) therefore is believed to be due primarily to the evaporation of moisture (~4 percent), to the volatilization and combustion of adsorbed organic components, and to the combustion of a relatively small portion of the powdered carbon (~2 percent).

TABLE 5. EXPERIMENTAL DATA SHOWING CARBON LOSSES DURING SEVERAL REGENERATION EXPERIMENTS

Expt. No.	Temp, F	Gas Composition	Average Feed Rate, g/min[a]	Relative Adsorptive Capacity	Weight Recovery, percent[a]	Carbon Losses,[b] percent
22	1000	Air	5.3	100	57	30.8
24	1000	96% N_2: 4% O_2	19.0	83	88	3.9
25	1000	98% N_2: 2% O_2	18.0	78	90	2.5
26	1200	98% N_2: 2% O_2	24.0	83	87	2.4
27	1500	98% N_2: 2% O_2	24.0	97	81	2.4

(a) Feed rate and weight recovery calculated on dry carbon basis.
(b) Based on CO_2 content of exhaust gas.

Comparison of Fluidization Techniques. In order to compare the two fluidization techniques for future development effort, preliminary calculations of the heat and material requirements were made for the proposed pilot-scale regeneration system, based on the production of 30 pounds of regenerated carbon in an 8-hour period assuming various levels of moisture in the feed.

The major results of the calculations indicate:

(1) Because a much lower gas velocity can be used to achieve fluidization, the heat requirements are substantially lower for the pulsed fluidized-bed system than for the inert-bed-type system. Sufficient heat, however, is available from combustion of propane in the inert bed system to allow processing of feed materials containing up to 50 percent H_2O. In the pulsed-bed system, by contrast, only enough combustion heat can be supplied to allow processing of feeds containing 3 percent moisture. Additional heat, for increased moisture contents, must be supplied externally, i.e., conduction through walls of vessel.

(2) The gas flow resulting from the evaporation of moisture in the feed can represent a substantial portion of the overall gas volume. In the inert bed system, enough flexibility is present to accommodate the increased gas flow. In the pulsed-bed system, however, the increased gas flow would result in the rapid elutriation of the bed material. This would prohibit the use of feed materials containing significant amounts of moisture unless feed rates were decreased by an order of magnitude.

Design, Construction, and Operation of a Pilot-Plant Facility

Design

The pilot-scale unit was designed on the basis of a nominal capacity of 30 pounds of regenerated carbon in 8 hours. A heat and materials flow diagram for the system is shown in Figure 9. Other essential data on which the design was based are shown in Table 6. These data were obtained from or indicated by the experimental work conducted during Phase I of the program or from past experience with systems similar in nature.

TABLE 6. MISCELLANEOUS DESIGN DATA

Item	Value	Source
Nominal capacity of unit, pounds of product per 8-hour day	30	FWPCA
Moisture content of carbon feed, percent	50	FWPCA
Superficial velocity for fluidization, fps at temperature	1.0	Experimental
Operating temperatures, F		
Firebox	2000	Experimental
Bed	1250	Experimental
Freeboard	1000	Experimental
Particle size of inert bed material, mesh	20x48	Experimental

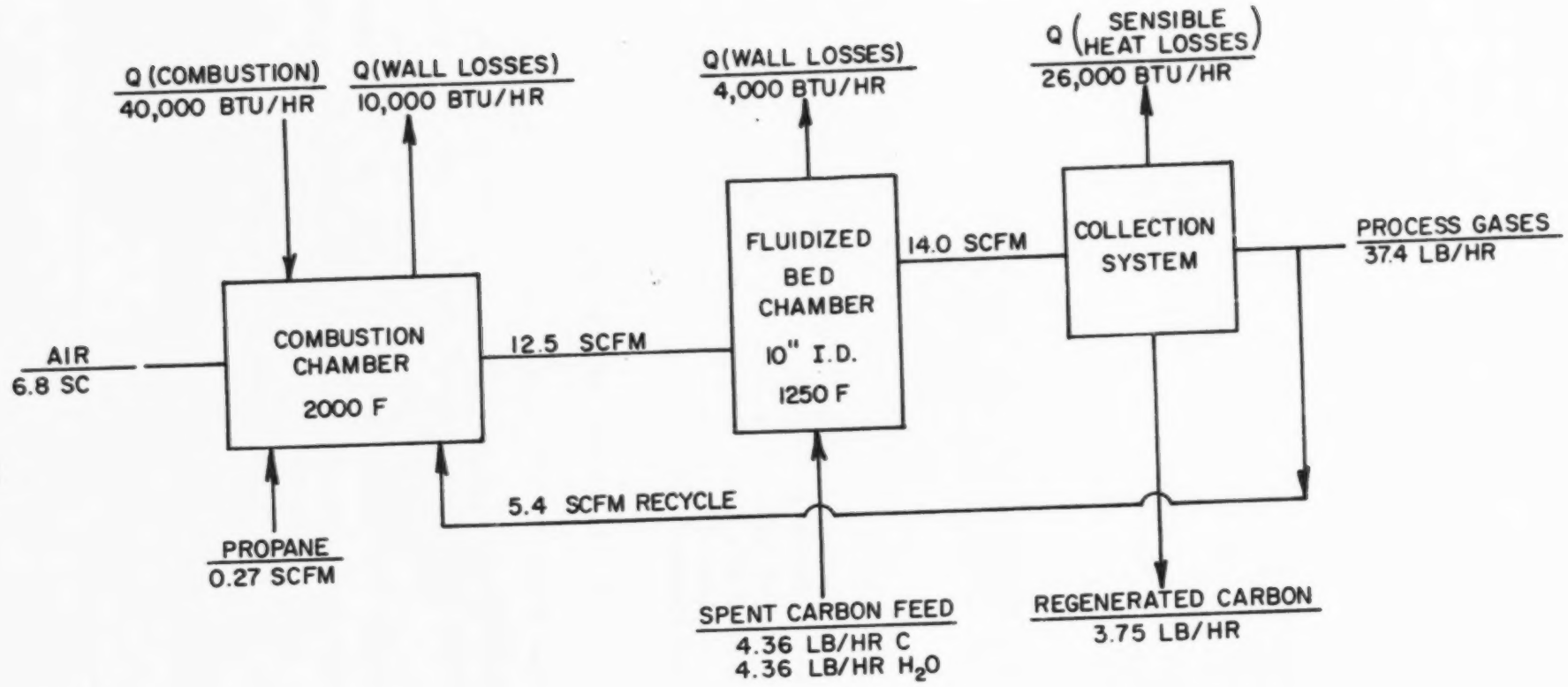


Figure 9. Heat and materials flow diagram for pilot regeneration system

TABLE 6. (Cont.)

Item	Value	Source
Bed depth, in.	12	Experimental
Available excess oxygen in exhaust gases, percent	1	Experimental

After the design and construction of the unit was completed, some modification was necessary due to the inability to easily produce carbon containing 50 percent moisture. These modifications included the addition of a port for introducing propane into the bed zone of the unit and the introduction of auxiliary air into the firebox instead of recycling the exhaust gases. The carbon product collection system also was changed from a dry system (cyclone) to a wet system (venturi scrubber). This was necessary to allow integration of the unit into the powdered carbon adsorption system.

Construction

The pilot-plant unit was constructed according to the drawing shown in Figure 10. The fluidized-bed vessel has an inside diameter of 10 in. and is 48 in. high. The unit has a burner-windbox section in which propane is burned with a slight excess of air to provide heat for evaporation of the water present in the feed. This section as well as the remainder of the unit is lined with a castable insulating refractory. A refractory orifice plate is used to separate the windbox gases from the fluidized-bed zone and to provide even distribution of the gases. The orifice plate contains 12-1/8-in. diameter orifices and is 4 in. thick.

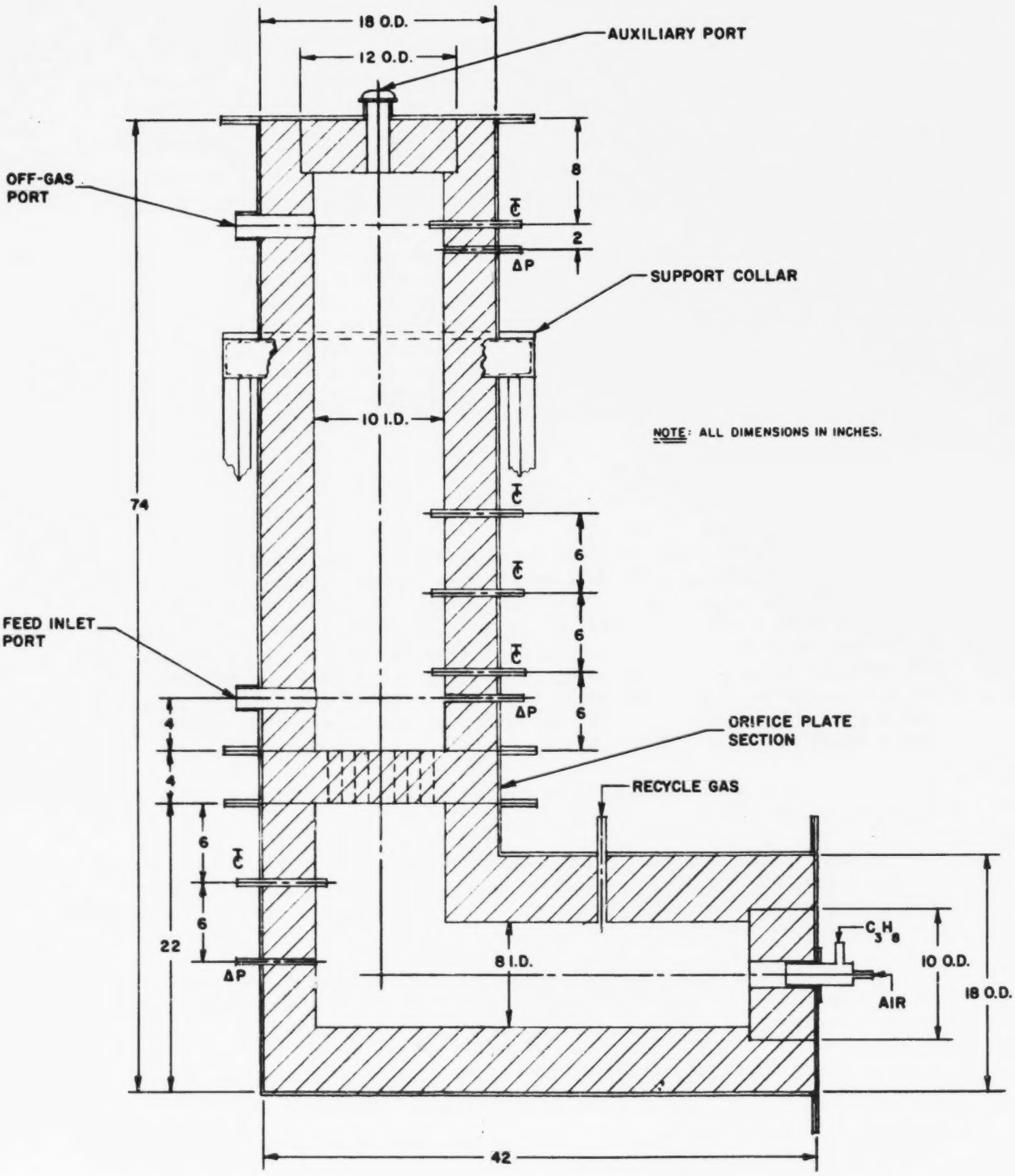
The carbon feed is introduced through the wall of the furnace using a vibratory screw feeder.

The exhaust gases bearing the regenerated carbon exit through an opening in the freeboard zone. They then enter a venturi type water scrubber where they are cooled and cleared of carbon. The gases are then exhausted to the atmosphere.

The entire unit is supported by an I-beam framework which is mounted on swivel casters. The unit can easily be disassembled without the use of power equipment.

The necessary instrumentation (temperature recorder, flowmeter, pressure gages, manometers, etc.) are mounted in a portable control console.

The arrangement of the fluidized-bed pilot plant and the necessary auxiliary equipment is shown in Figure 11.



NOTE: ALL DIMENSIONS IN INCHES.

Figure 10. Detailed drawing of the 10-inch-diameter fluidized-bed unit

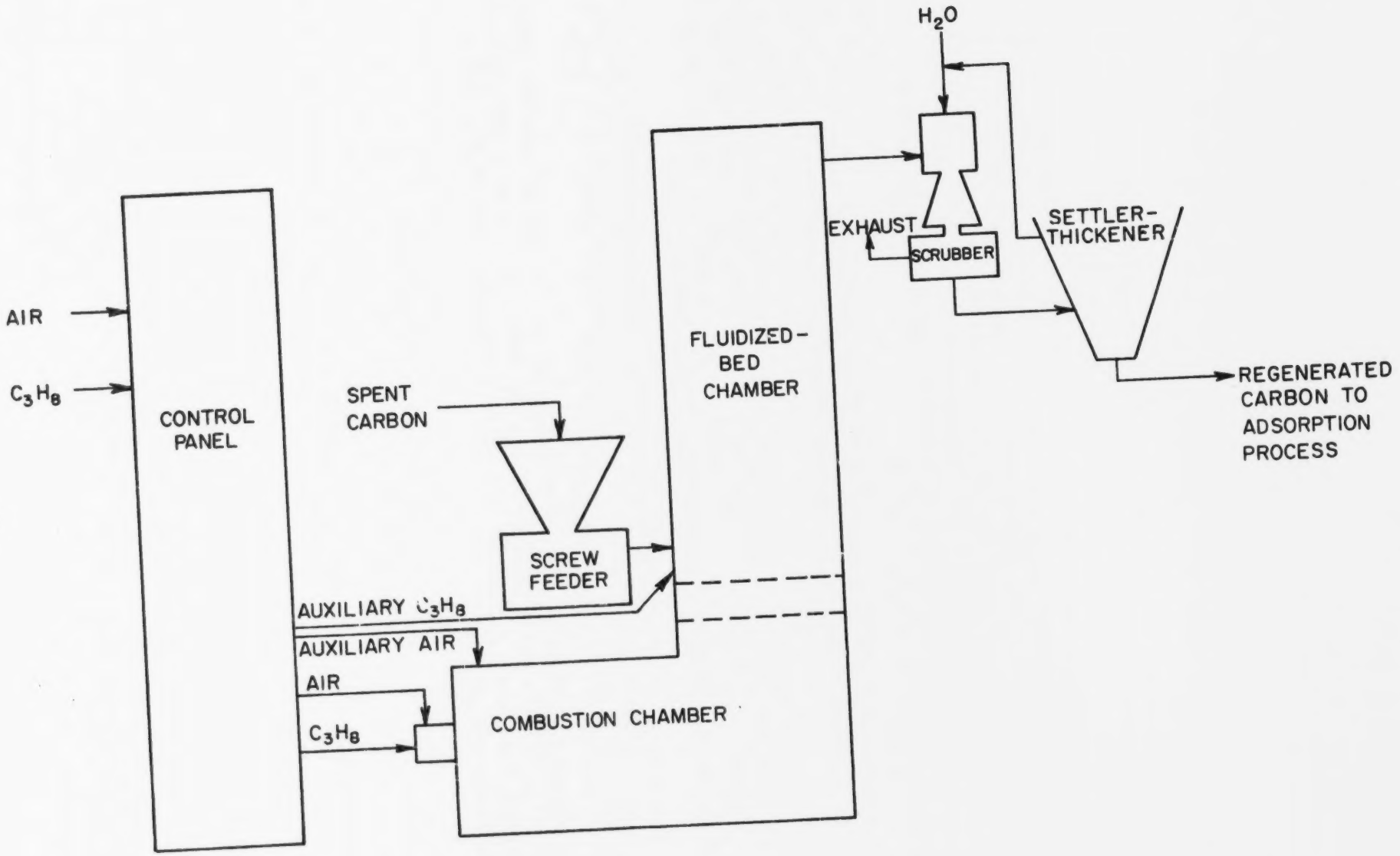


Figure 11. Arrangement of equipment for pilot-plant regeneration study

Operation

Procedure. In an effort to check out the pilot-plant equipment prior to initiating a long-term integrated run, in which the carbon was recycled through the entire adsorption system, the regeneration unit was operated in a batchwise manner for several runs. During this "shake-down" period, a total of eleven separate experiments were conducted--eight with virgin carbon and three with spent carbon.

The procedure used to evaluate the carbon regeneration efficiency is described below.

Secondary effluent was continuously contacted with 200 mg/l of powdered carbon in a two-stage countercurrent mixer-settler and filtration operation. The spent carbon slurry was then concentrated in a thickener and centrifuge. The concentrated spent carbon was then fed to the fluidized-bed regeneration furnace. The regenerated carbon was then recovered from the venturi-type scrubber in a thickener and reused in the powdered carbon adsorption system.

Samples of the secondary effluent feed to the system as well as samples of the effluent from the adsorption system were analyzed for turbidity and total organic carbon (TOC). Samples of the spent carbon and regenerated carbon were collected and analyzed for solids content (dried at 106 C for 24 hrs), volatiles (400 C for 2 hrs), ash content (oxidizing at 800 C to constant weight), and fixed carbon (weight of volatiles and ash subtracted from the dried weight).

The recovery of carbon from the regeneration furnace is based on the fixed-carbon analyses.

Results and Discussion. The objectives of the shakedown period were: evaluation of the equipment; training of FWPCA operators; and assessment of carbon lost upon regeneration. The conditions used during these experiments are shown in Table 7.

TABLE 7. CONDITIONS EMPLOYED DURING PILOT-PLANT START-UP OPERATIONS

Run No.	Temperature, F[a]		Gas, scfm		Fluidizing Velocity, fps[b]	Exhaust Gas O_2 Content, percent	Feed	
	Firebox	Bed	Air	Propane			Type	Rate, lb/hr[c]
1	1700	1500	11.5	0.42	1.35	(d)	Spent	3.8
2	1750	1605	9.0	0.34	1.06	(d)	Spent	2.4
3	1785	1470	9.7	0.35	1.18	(d)	Virgin	4.2
4	2240	1440	8.3	0.36	0.95	2.0	Virgin	1.5
5	2240	1465	8.3	0.36	0.96	1.8	Virgin	1.6

TABLE 7. (Cont.)

Run No.	Temperature, F[a] Firebox	Bed	Gas, scfm Air	Propane	Fluidizing Velocity, fps[b]	Exhaust Gas O_2 Content, percent	Feed Type	Feed Rate, lb/hr[c]
6	2300	1335	7.5	0.38	0.82	1.8	Virgin	1.8
7	2340	1325	7.3	0.38	0.79	1.9	Virgin	2.0
8	2300	1290	7.5	0.33	0.79	1.3	Virgin	1.7
9	2190	1295	8.5	0.38	0.91	0.8	Virgin	2.0
10	2235	1210	8.5	0.37	0.87	1.0	Virgin	(e)
11	2210	1255	8.2	0.33	0.84	0.4	Spent	3.1

(a) Temperatures are reported as average throughout the feeding period.
(b) Velocity is reported as average.
(c) Feed rate is reported as average pounds per hour on dry solids basis.
(d) Exhaust gas was not monitored for O_2 content during these runs.
(e) Due to malfunction of feeder, a feed rate cannot be calculated.

During the first three experiments (in which evaluation of the equipment was the major objective), the oxygen content of the exit gases was not determined, and probably was relatively high. Carbon losses due to combustion were quite high in those experiments (Table 8).

TABLE 8. RESULTS OBTAINED DURING PILOT-PLANT START-UP OPERATIONS

Run No.	Solids Fed Total, lb	Solids Content, percent	Dry, lb	Solids Recovered Dry, lb	Percent
1	80.0	23.9	19.13	7.49	39.3[a]
2	75.0	23.6	17.68	4.82	27.3[a]
3	100.0	29.3	29.30	17.26	58.9[a]
4	51.0	27.2	13.86	10.45	75.4
5	69.5	27.9	19.40	15.75	81.2
6	67.6	27.1	18.30	17.20	94.0
7	73.2	26.9	19.68	13.68	69.6
8	50.0	26.9	13.45	12.46	92.6
9	27.5	25.9	7.12	5.40	75.9
10	37.5	26.8	10.05	8.92	88.7
11	81.0	29.1	23.60	17.50	74.2

(a) Oxygen contents of exhaust gases were not monitored during runs 1, 2, and 3. During the other runs, the gases were analyzed using a Leeds and Northrup Thermomagnetic Oxygen Analyzer.

In all of the subsequent runs, the oxygen concentration in exit gases was measured and controlled. The results of these experiments also are shown in Table 8. The percentage of solids recovered during the experiments with virgin carbon in which the oxygen content was monitored varied in individual runs from a low of about 69 percent to a high of about 94 percent. The wide variation in recovery from run to run is believed to be due to the hold up of solids in the scrubbing system, particularly in the baffled entrainment separator. This belief is supported by the solids recovery data shown for Runs 6, 7, and 8, all of which were run under substantially the same conditions. The percentages of solids recovered in Runs 6 and 8 were somewhat higher than expected (94 and 92.6 percent, respectively), while the recovery in Run 7 was much lower than anticipated (69.6 percent). A review of the procedure employed in these runs revealed that after Run 6 the scrubbing system was flushed and drained overnight, whereas after Run 7 flushing was conducted for only about several hours. It is believed that the product yield from Run 6 included carryover from Run 5, and that a few pounds of the product from Run 7 was not washed from the system. This material later reported in the product from Run 3, in which more thorough flushing was employed. A more nearly accurate idea of carbon losses due to combustion can be obtained by using the combined material balance data from the seven runs in which virgin carbon was treated and in which the oxygen content of the exit gases was controlled (Runs 4 through 10). The total amount of carbon fed during these experiments was 101.86 pounds. Total carbon recovered in the same runs was 83.86 pounds. The average recovery of solids calculated on this basis was 82.3 percent.

Samples of the feed and regenerated carbon from these seven runs were analyzed by FWPCA for fixed carbon content. Fixed carbon in the feed was 89.3 percent, and the regenerated product 92.8 percent. The calculated recovery of carbon on this basis was 85.6 percent.

The fluidized-bed regeneration unit was operated as an integrated part of the adsorption system for a period of 23 days. During this time 21 barrels of spent carbon slurry were concentrated in the centrifuge to approximately 25 percent solids and regenerated for recycle to the system. The average operating conditions used during this time are shown in Table 9.

As can be seen from the data in this table, the operating conditions were quite constant throughout the study. The average mean operating parameter values of the entire run are as follows:

Firebox temperature, F	2204
Bed temperature, F	1257
Freeboard temperature, F	1084
Fluidizing velocity, fps	0.84
Feed rate (wet), lb/hr	7.37
Solids content of feed, percent	24.76
Exhaust gas oxygen content, percent	0.69

TABLE 9. AVERAGE OPERATING PARAMETERS DURING REGENERATION RUN

Date	Barrel Number	Temperature, F			Fluidizing Velocity, ft/sec	Exhaust Gas Oxygen, percent	Feed	
		Firebox	Bed	Freeboard			Rate, lb/hr	Solids, percent
Nov. 17	1	2202	1203	1048	0.79	0.82	9.68	22.81
Nov. 18 & 19	2	2223	1246	1066	0.81	0.58	7.28	23.40
Nov. 19 & 20	3	2198	1346	1161	0.88	0.88	--	23.20
Nov. 21	4	2216	1162	997	0.80	0.96	7.92	22.80
Nov. 22 & 23	5	2188	1255	1082	0.85	0.35	7.85	24.85
Nov. 24	6	2227	1285	1107	0.86	0.57	7.30	26.10
Nov. 25 & 26	7	2204	1234	1064	0.84	1.30	9.30	24.65
Nov. 28 & 29	8	2195	1265	1091	0.85	0.72	8.10	24.83
Nov. 30	9	2221	1296	1114	0.87	0.53	6.04	24.60
Dec. 1	10	2233	1263	1093	0.83	--	8.33	25.02
Dec. 2	11	2220	1266	1087	0.86	0.55	--	25.67
Dec. 2 & 3	12	2239	1293	1136	0.76	0.36	5.77	25.59
Dec. 3	13	2198	1250	1068	0.84	--	7.18	26.29
Dec. 4	{14 / 15}	2014	1264	1123	0.88	0.13	8.65	{26.42 / 26.71}
Dec. 5	16	2038	1249	1088	0.85	0.40	9.90	23.55
Dec. 6	17	2229	1254	1084	0.85	0.86	7.46	24.23
Dec. 7	18	2240	1270	1090	0.86	1.30	9.12	26.87
Dec. 8	19	2256	1244	1072	0.83	0.70	8.20	23.76
Dec. 9	20	2269	1262	1098	0.85	0.73	7.50	24.16
Dec. 16	21	2262	1228	1004	0.75	--	6.03	24.40

The fluidizing air to propane ratio was adjusted to give less than 1 percent available oxygen in the exhaust gases. The average total gas flow to the unit was about 8 scfm.

During the integrated run, the effluent from the carbon adsorption system as well as the secondary effluent feed (influent to adsorption system) was sampled periodically and analyzed for total organic carbon content and turbidity. Figure 12 shows the daily average total organic carbon content of the influent as compared to that of the effluent from the adsorption system. The large fluctuation in the secondary effluent quality which was fed to the system can readily be seen. However, the TOC removal by powdered activated carbon even after 2 or 3 regeneration cycles remained relatively constant. The data in this figure also show that the regeneration was operated for a period of time long enough for the powdered carbon to be regenerated 3.6 times. It does not appear that total organic carbon removal efficiencies are greatly affected by the number of regeneration cycles.

Table 10 gives the average total organic carbon (TOC) values of the treated effluent for each regeneration cycle as well as for virgin carbon. Also given is the percentage of TOC removal for each cycle. It can be seen that the TOC removal efficiency did not change appreciably after several regeneration cycles, even though the quality of the influent was much poorer. It can also be seen that the TOC removal efficiency of regenerated powdered carbon compares favorably with virgin carbon.

The curves in Figure 13 represent the turbidity level of both the feed to the adsorption system and the effluent. It can be seen that the turbidity removal in the powdered carbon adsorption system is a reflection of the secondary effluent feed to the system. That is, when the turbidity level of the feed was high the turbidity level of the effluent increased accordingly. Although the turbidity data are somewhat erratic, it would appear that the number of regeneration cycles does not adversely affect turbidity removal.

TABLE 10. AVERAGE TOTAL ORGANIC CARBON (TOC) VALUES AND REMOVAL EFFICIENCY FOR EACH REGENERATION CYCLE

Number of Regeneration Cycles	Total Organic Carbon		TOC Removal, percent
	Influent, mg/l	Effluent, mg/l	
0	12.9	2.5	80.6
1	9.3	2.7	70.9
2	21.7	4.4	79.4
3	27.0	4.2	84.4
3.6	14.5	3.7	74.5
0	23.5	3.6	84.7

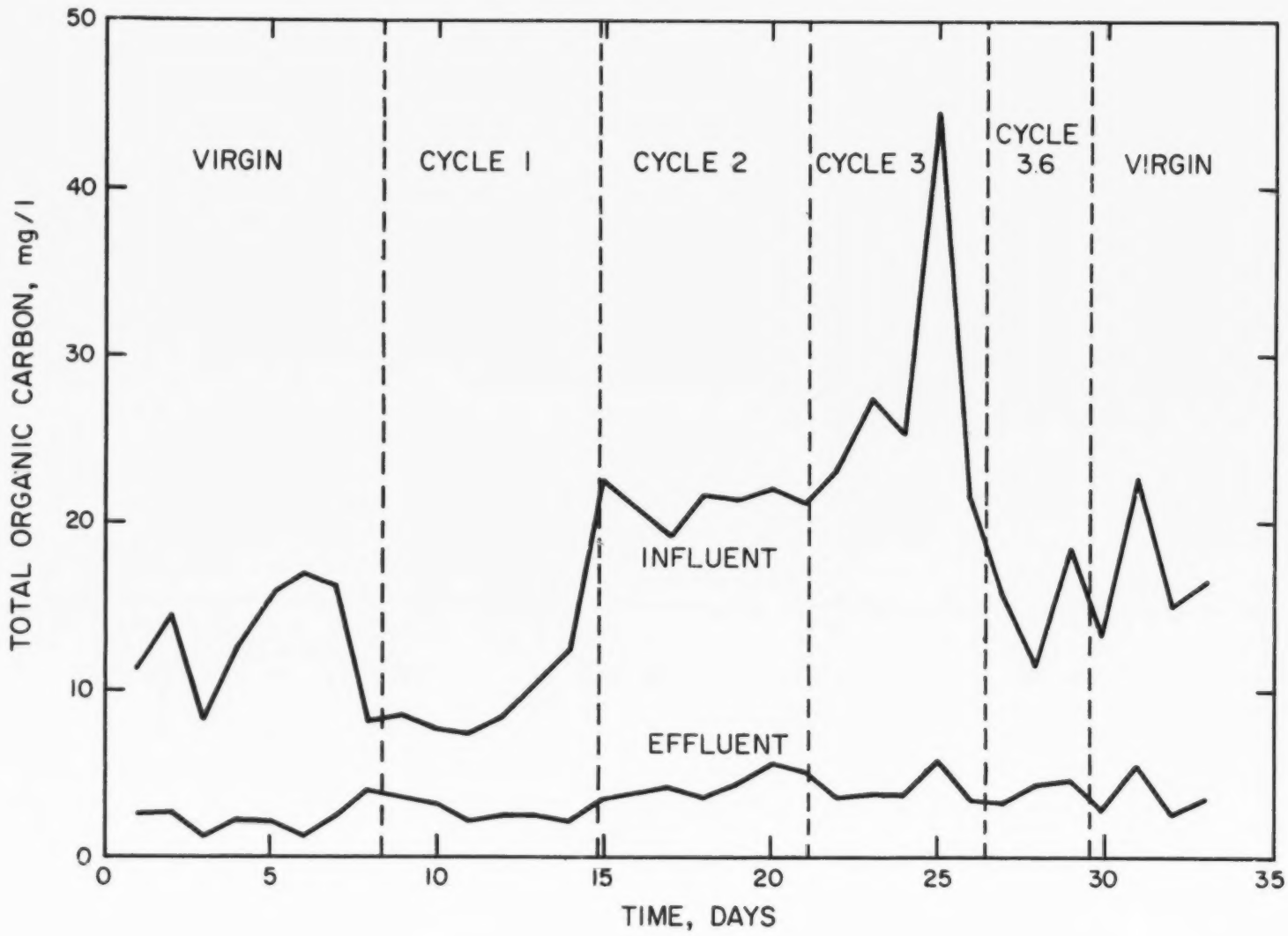
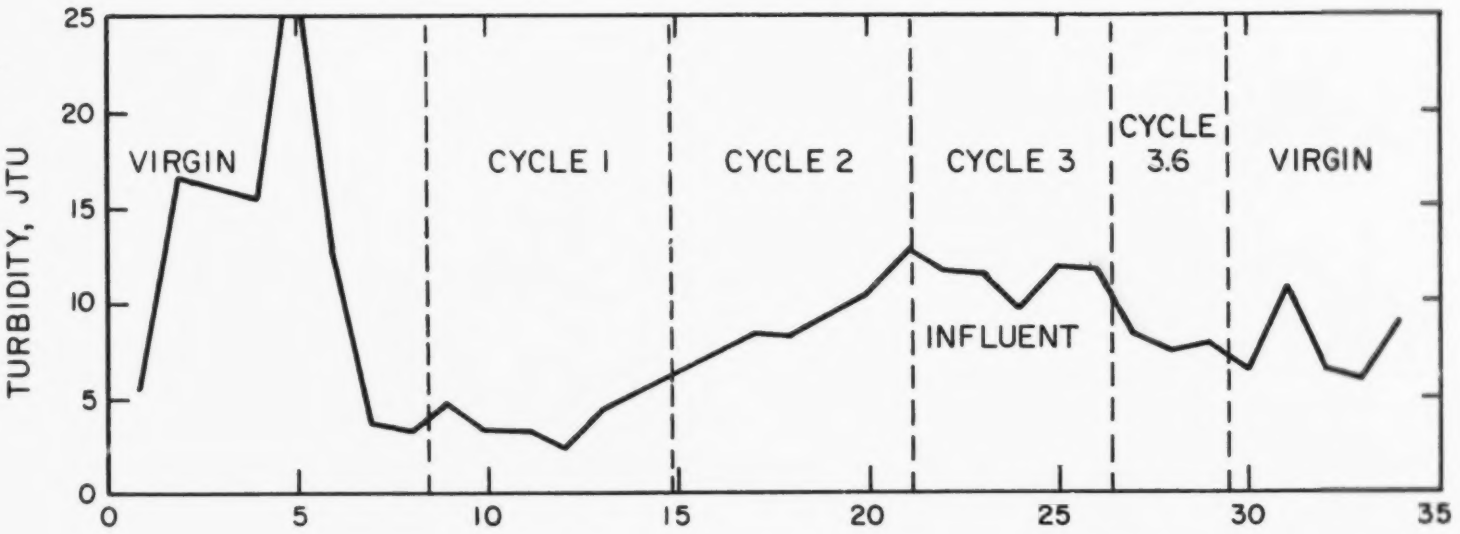


Figure 12. Total organic carbon removal using regenerated powdered carbon



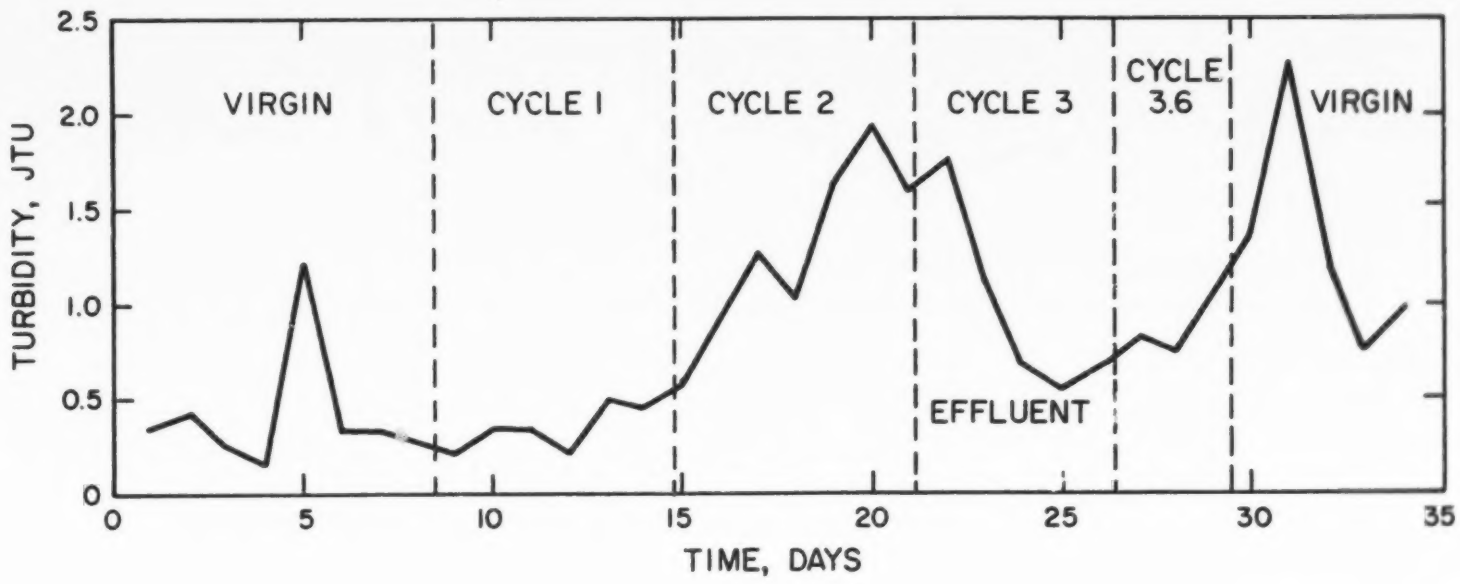


Figure 13. Turbidity removal from secondary effluent using regenerated powdered carbon

Table 11 compares the average TOC removal by regenerated carbon to virgin carbon for the entire run. In both cases the adsorption efficiency is essentially the same.

TABLE 11. COMPARISON OF AVERAGE TOTAL ORGANIC CARBON REMOVAL BY VIRGIN AND REGENERATED CARBON

	Average Total Organic Carbon in Effluent, mg/l	Total Organic Carbon Removal, percent
Virgin carbon	4.18	76.6
Regenerated carbon	3.43	79.7

As was stated earlier the regenerated carbon was sampled and analyzed for ash content, volatiles, and fixed carbon content. These data as well as the amount of fixed carbon recovered from each drum of material processed is shown in Table 12. It can be seen that as the run progressed the fixed carbon content of the regenerated carbon decreased while ash content increased and the volatiles remained fairly constant. This effect is shown graphically in Figure 14.

The carbon recovery on a fixed carbon basis varied from drum to drum from a low of 66 percent to a high of 106 percent. The values indicate a mean carbon recovery and average carbon recovery of approximately 86 percent. Material balance data also were obtained for the entire run which indicated that 81.8 pounds of fixed carbon were recovered compared to an initial input of 148.8 pounds of fixed carbon. Thus, the overall recovery through 3.6 cycles of adsorption and regeneration was 54.9 percent or, on the basis of 1 regeneration cycle, 84.6 percent.*

Problems Encountered. During the startup period and during the integrated run, a few relatively minor problems were encountered. The first problem encountered was with the vibratory screw feeder. As was stated earlier, the unit was designed to regenerate carbon at 50 percent solids and when the 25 percent solids feed was used some minor modifications were required.

Another problem was with the sand bed being carried over into the scrubber and carbon recovery system. This problem was encountered throughout the run and is believed to be due to the short freeboard** section of the fluidized-bed furnace. Overall the entire system, including furnace, scrubber, and recovery system, performed satisfactorily throughout the run.

*Note: Fraction recovered for entire run equals $x^{3.6}$, where x is the fraction recovered per regeneration cycle.

**The space in the furnace above the expanded bed.

TABLE 12. DAILY REGENERATED CARBON ANALYSES AND RECOVERY

Barrel Number	Spent Carbon Feed: Dry Basis, lb	Percent: Fixed C	Ash	Volatile	Fixed C, lb	Regenerated Carbon Recovered: Dry Basis, lb	Percent: Fixed C	Ash	Volatile	Fixed C, lb	Recovery, percent
1	26.5	82.1	7.9	10.0	21.76	21.37	89.2	9.1	1.7	19.06	87.6
2	26.5	82.6	7.9	10.5	21.89	31.98	92.2	6.7	1.1	29.33	65.9
3	28.7	78.7	7.3	14.0	22.59		91.2	8.1	0.7		
4	36.3	86.7	6.9	6.4	31.41	37.41	89.3	8.4	2.3	33.41	106.2
5	39.1	83.6	7.7	8.7	32.69	36.21	90.7	7.9	1.4	32.84	100.5
6	37.7	83.9	8.1	8.0	31.63	27.79	90.2	8.3	1.5	25.21	79.7
7	24.1	83.4	8.4	8.1	20.10	20.81	90.3	8.8	0.9	18.88	93.9
8	39.42	82.8	7.9	9.3	32.64	28.84	90.0	7.9	2.1	25.96	79.5
9	28.23	81.0	9.5	9.5	22.87	43.48	88.6	10.3	1.1	38.44	81.0
10	30.02	81.9	9.4	8.7	24.59		88.2	10.3	1.5		
11	14.31	82.6	9.3	8.1	11.82	26.83	87.8	11.1	1.1	23.56	82.9
12	21.88	75.9	11.5	12.6	16.61						
13	23.60	75.4	11.2	13.4	17.79	18.29	86.4	11.3	2.3	15.80	75.0
14	4.23	77.3	11.2	11.5	3.27	16.07	87.1	12.4	0.5	14.00	72.5
15	21.03	76.3	12.3	11.4	16.05						
16	20.14	75.6	12.4	12.0	15.23	16.39	84.1	13.2	2.7	13.78	90.5
17	22.60	74.9	12.2	12.9	16.93	17.86	86.6	12.3	1.7	15.31	90.4
18	10.61	74.3	12.3	13.3	7.88	23.91	85.1	12.7	2.2	19.89	91.5
19	19.96	69.4	15.1	15.5	13.85		81.2	16.4	2.4		
20	24.46	76.3	13.3	10.4	18.66	20.84	81.6	14.2	4.2	17.01	91.2

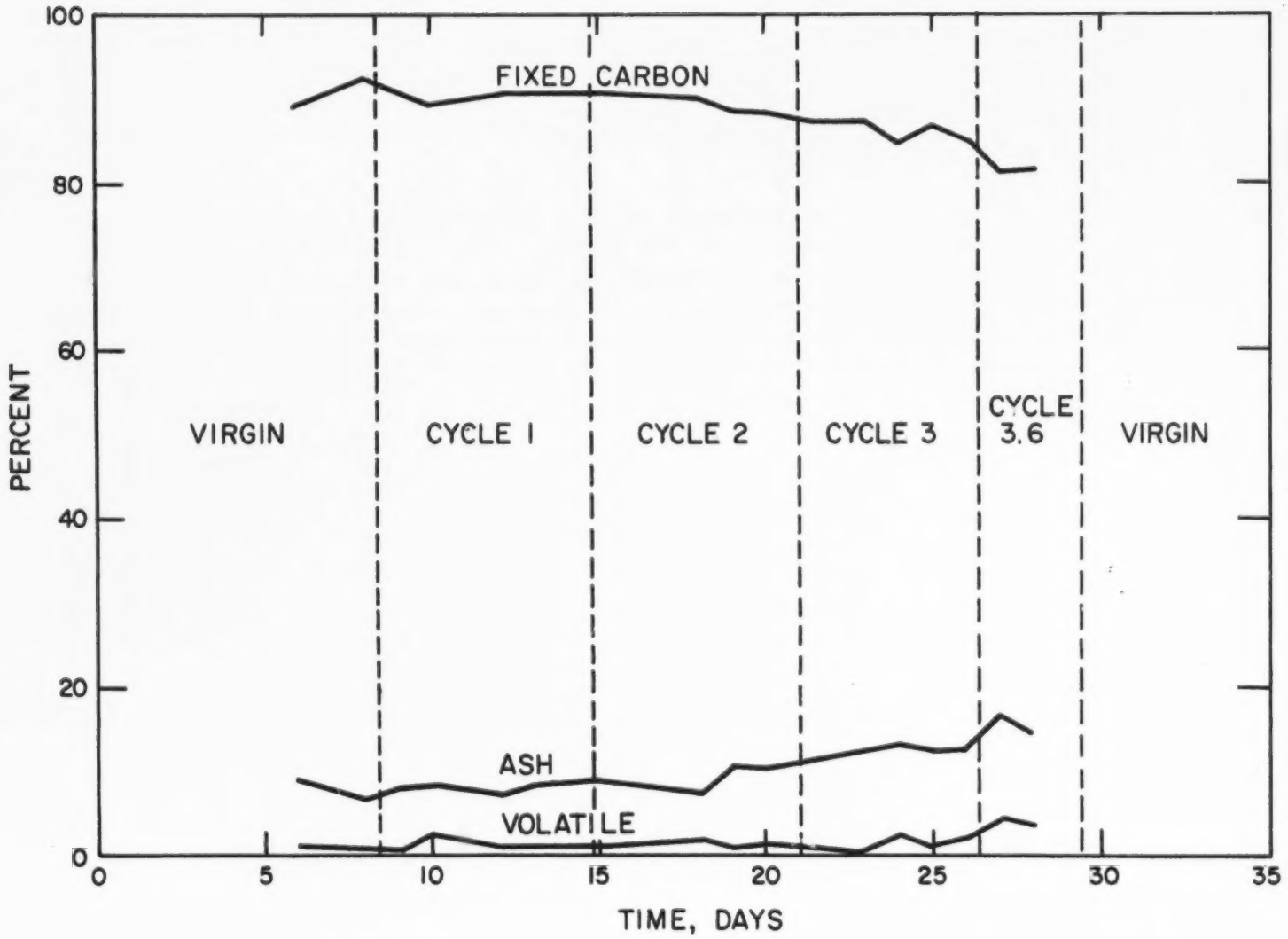


Figure 14. Fixed carbon, ash, and volatile content of regenerated carbon

As was stated in the results section, about 15 percent of the carbon was lost during each regeneration cycle. The exact reason for this is not known. It is felt, however, that the carbon losses were not due to combustion since an average of only 0.56 percent excess oxygen was available to support such combustion. The possibility of carbon losses in the exhaust gases also was investigated briefly. The use of a porous bag filter over the exhaust stack showed only about 0.1 percent of the carbon being carried out in this stream. There is also the possibility of physical carbon losses due to handling, etc., but every effort was made to hold this at a minimum through the run.

The TOC removal efficiency of the regenerated carbon is considered to be quite good even after 3.6 regeneration cycles. The average effluent TOC values for virgin and regenerated carbon, overall, were 3.1 and 3.8 mg/l, respectively. The influent feed to the adsorption system had an average TOC level of 18.1 mg/l.

The overall physical performance of the fluidized-bed regeneration furnace was quite good throughout the study. This is substantiated by the fact that on more than one occasion the unit was operated unattended overnight with no problems being encountered. Even though the feed rates attained during the study were somewhat lower than anticipated, due to the increase in moisture content of the feed, it is felt that the pilot-scale study was quite successful.

DESIGN AND ECONOMIC CONSIDERATIONS

In order to compare the economics of powdered carbon adsorption to other processes, a preliminary evaluation of a commercial fluidized-bed regeneration system was made. The evaluation was based on a plant having a production capacity of 20,000 pounds per day of regenerated carbon with feed slurry containing 25 percent solids. The pilot-plant study indicates that this feed composition can be produced by a single centrifugation of the spent carbon slurry as it leaves the adsorption system. After centrifuging, the feed would be introduced into a fluidized-bed regeneration unit containing an inert bed at about 1250 F. Recovery of the regenerated carbon was conservatively estimated at about 85 percent per regeneration cycle which is approximately the same as that achieved in pilot-plant work.

The major uncertainty concerning the design of the commercial system is the feasibility of direct combustion of natural gas within the fluidized-bed chamber. This type of operation is the preferred method since it provides more efficient heat utilization and combustion chamber temperatures generally less than 2000 F. Direct combustion within the bed, however, may result in increased losses of carbon through combustion. This aspect was not evaluated sufficiently in pilot-plant studies because the unit was small enough to permit essentially complete combustion within the combustion chamber while maintaining temperatures below the design limits of the unit. However, the required operating methods in larger scale equipment remains to be investigated.

To cover an alternative operating procedure, design calculations were made of two basic systems; one in which natural gas would be burned directly in the fluidized-bed zone and the other in which complete combustion would be obtained in the combustion chamber and temperatures would be reduced to a practical limit (2000 F) by off-gas recycle. Flow diagrams illustrating the two examples are shown in Figures 15 and 16. Pertinent data concerning the design calculations are listed in Table 13.

TABLE 13. CONDITIONS AND RESULTS OF EXAMPLE DESIGN CALCULATIONS FOR COMMERCIAL REGENERATION SYSTEM

	Example I (conventional operation)	Example II (off-gas recycle)
Basis:		
Capacity, lb/day	20,000	20,000
Recovery per cycle, %	85	85
Operating Conditions:		
Slurry feed rate, lb/hr	4,000	4,000
Combustion chamber temperature, F	2,000	2,000

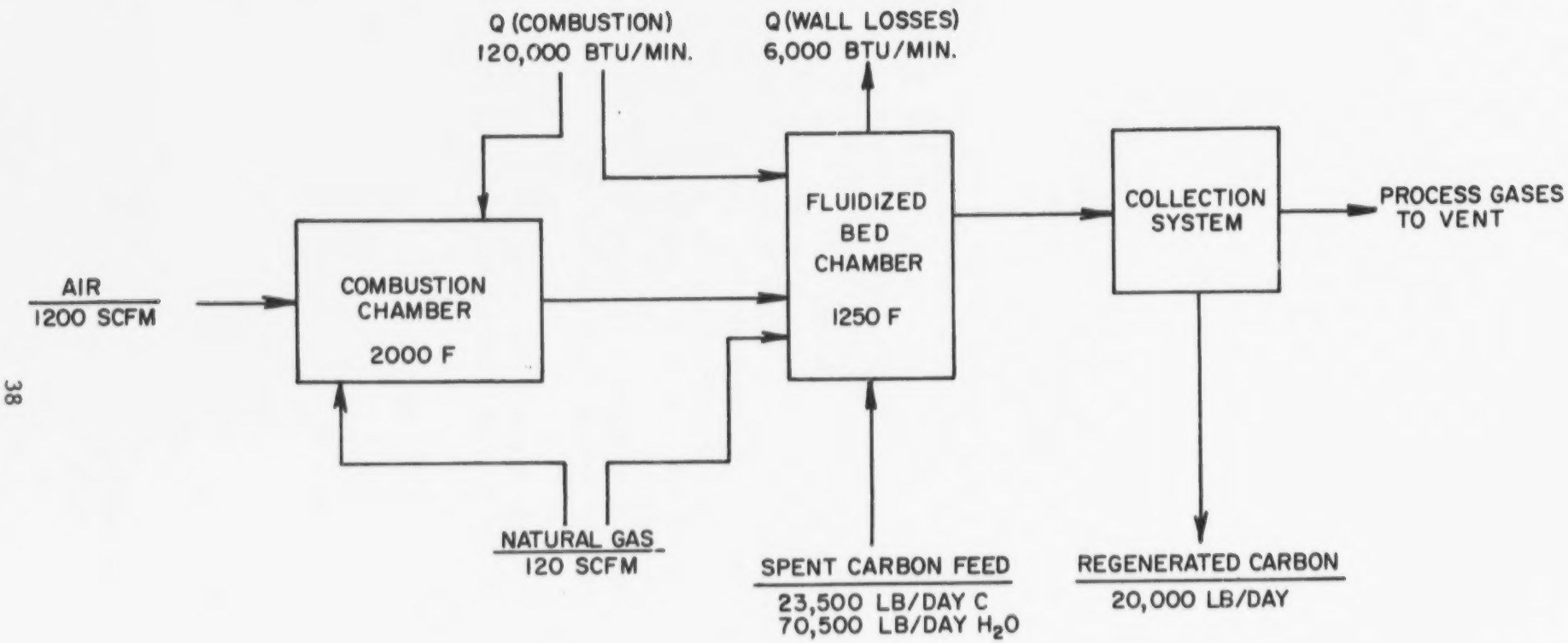


Figure 15. Flow diagram of commercial regeneration system, employing conventional operation, example I

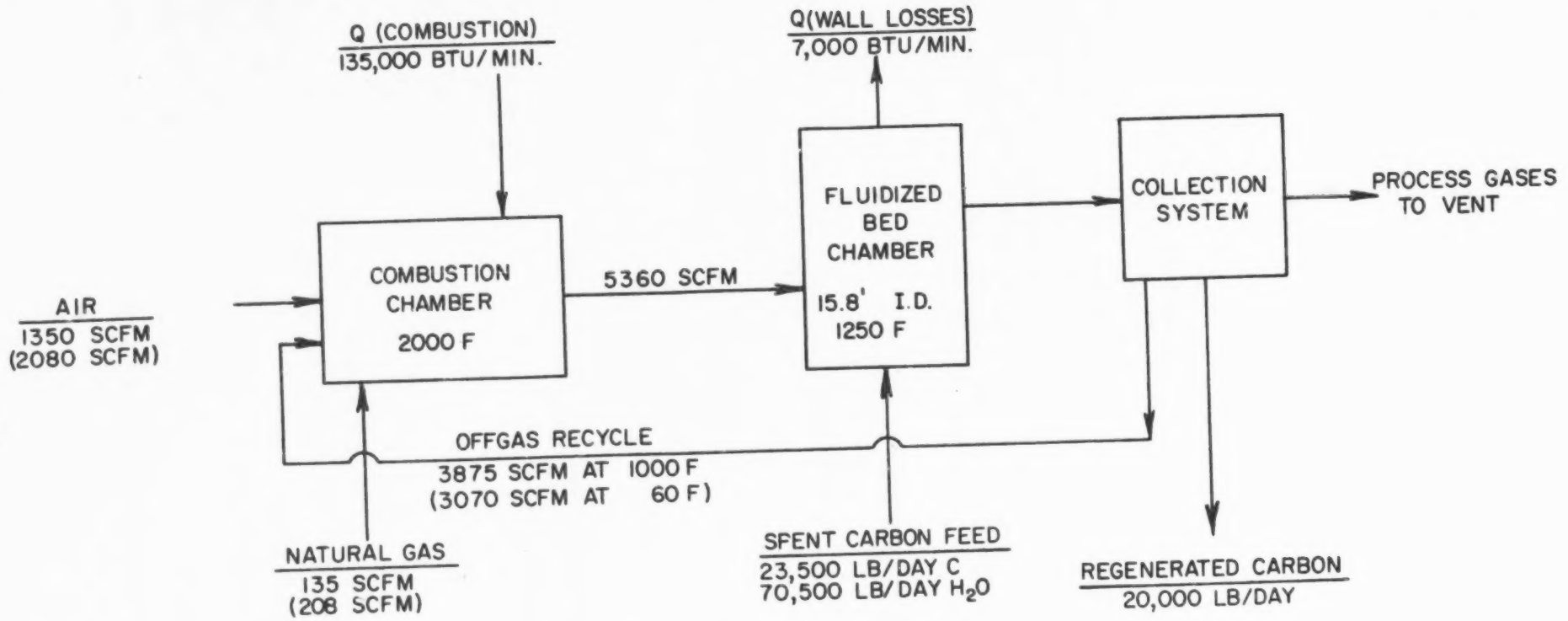


Figure 16. Flow diagram of commercial regeneration system employing offgas recycle, example II

TABLE 13. (Cont.)

	Example I (conventional operation)	Example II (off-gas recycle)
Operating Conditions (cont.):		
Bed temperature, F	1,250	1,250
Fluidizing velocity, fps	1.0	1.5
Calculated Data:		
Heat requirement, million Btu/hr	7.2	8.1
Bed diameter, ft	9.6	15.8

The results of the calculations indicate that a regeneration unit of 10- to 15-foot diameter would be required to produce 20,000 pounds per day of regenerated carbon. A detailed drawing of the unit is shown in Figure 17. Itemized estimates of the capital and operating costs for the installation are shown in Tables 14 and 15. These data indicate that capital costs range from $351,000 to $434,000. Plant operating costs would be 0.9 cents to 1.1 cents per pound of carbon.

TABLE 14. CAPITAL COSTS FOR COMMERCIAL REGENERATION SYSTEM

	Cost, dollars	
	Design Example I	Design Example II
Essential Plant Costs		
1. Complete Fluidized Bed Unit	150,000	200,000
2. Centrifuge	60,000	60,000
Total PIE (Principal Items of Equipment)	210,000	260,000
3. Erection and Assembly of Plant @ 30% of PIE	63,000	78,000
4. Instrumentation @ 4% of PIE	8,000	10,000
Total Essential Plant Costs	281,000	348,000
Other Plant Costs		
5. Contingencies @ 10% of above items	28,000	35,000
6. Engineering @ 10% of above items	31,000	38,000
Total Plant Investment	340,000	421,000
7. Working Capital for 60 days Operation	11,000	13,000
Total Capital Costs	351,000	434,000

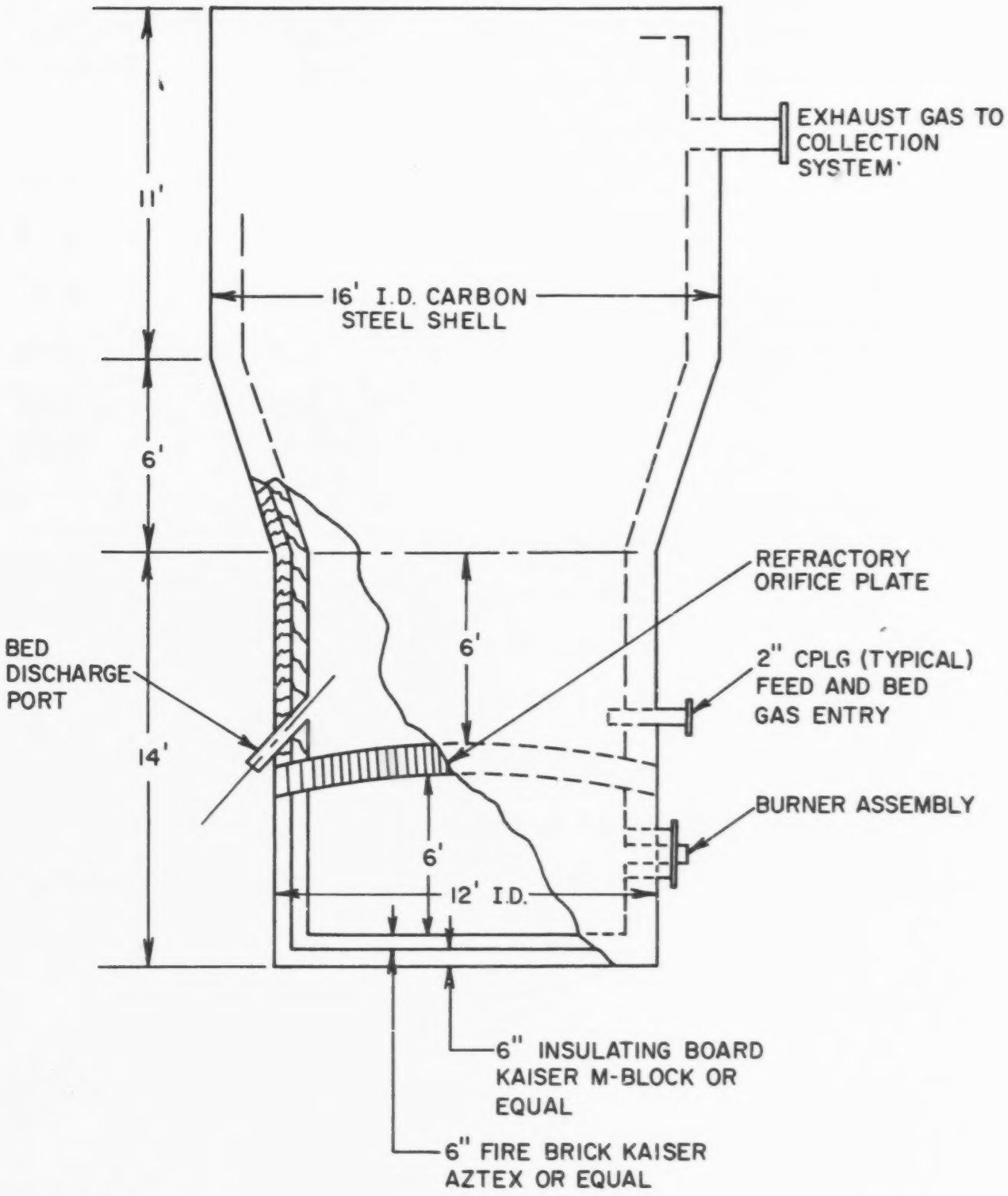


Figure 17. Detailed drawing of commercial fluidized-bed regeneration unit

TABLE 15. OPERATING COSTS FOR COMMERCIAL REGENERATION SYSTEM

	Cost per Stream Day, dollars	
	Design Example I	Design Example II
Essential Operating Costs		
1. Fuel @ $.25 per million BTU	43.20	48.50
2. Electric Power @ $.007 per KWH	8.40	8.40
3. Supplies and Maintenance Materials @ 0.0015% of Total Plant Investment	5.10	6.30
4. Operating Labor @ 8 man-hr per day, $2.00 per man-hr	16.00	16.00
5. Maintenance Labor @ 0.0015% of Total Plant Investment	5.10	6.30
6. Payroll Extras @ 15% of Items 4 and 5	3.20	3.30
Total Essential Operating Costs	81.00	88.80
Other Operating Costs		
7. Overhead, General and Administrative @ 30% of Items 4, 5, and 6	7.30	7.70
8. Amortization @ 0.0224% of Total Plant Investment	76.10	94.20
9. Taxes and Insurance @ 0.006% Total Plant Investment	20.40	25.20
10. Interest on Working Capital @ 0.725% of Above 9 Items	1.30	1.60
Total Operating Costs	186.10	217.50

Total Cost per Pound of Regenerated Carbon: 0.9-1.1¢

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* * * * * * *

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